

**ABSTRACT:**

Title of Dissertation: INTEGRATED ECONOMIC DECISION SUPPORT SYSTEM MODEL FOR DETERMINING IRRIGATION APPLICATION AND PROJECTED AGRICULTURAL WATER DEMAND ON A WATERSHED SCALE.

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This study involves the development of an irrigation economic model used to determine the estimated net benefit of various irrigation systems when used in temperate zones. The model processes SWAT (Soil and Water Assessment Tool) output data together with user supplied economic data as a basis for identifying agricultural fields likely to result in the greatest economic return for irrigation installations, based on irrigation installation costs, water costs, and the expected revenue from increased yields due to applied water. The model is capable of not only identifying those agricultural fields within the area of interest likely to result in the greatest net benefit, but is able to prescribe the most profitable irrigation system from an array of possible systems, based on user supplied economic and performance data. The model can also be used to determine the optimal average monthly irrigation volume to be applied to a given field, by balancing the expected revenue due to the estimated yield increase as a result of irrigation application versus the cost of water. The model is applied in this study to a

range of water cost levels and crop types from which general conclusions about the use of irrigation in temperate zones are made.

The primary product of this study is an irrigation economic tool capable of determining the profitability of irrigation installations versus non-irrigated systems for a wide range of hydrological and environmental conditions. The project included the collection and compilation of required data on land-use, topography, and soil properties, into a GIS project, used as a data input basis for the SWAT model. For demonstration purposes the model is applied to the Pocomoke River basin located in the Coastal Plain of Maryland's Eastern Shore. Input data for the model is taken from multiple SWAT simulations for various crops, modeled with a statistically generated artificial weather pattern typical of the region. Further analysis is conducted on the environmental impact of irrigation, using SWAT model simulations over a range of irrigation application levels. General conclusions are drawn on the effects of irrigation on water quality parameters and the nutrient/sediment transport processes involved.

**INTEGRATED ECONOMIC DECISION SUPPORT SYSTEM MODEL  
FOR DETERMINING IRRIGATION APPLICATION  
AND PROJECTED AGRICULTURAL WATER DEMAND  
ON A WATERSHED SCALE**

By:

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University of Maryland, College Park, in partial fulfillment  
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## **DEDICATION**

I would like to dedicate this work to my parents, Nabil and Dora Hanna, whose love and guidance has been constant source of joy and happiness throughout my life; and to my wife, Saoussan, for her patience and loving support during the preparation of this work.

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## LIST OF SYMBOLS AND ABBREVIATIONS:

$a$	= empirical coefficient
$A$	= watershed area [ha]
$A_{HRU}$	= area of the hydrologic response unit [km <sup>2</sup> ]
$a_1$	= empirical coefficient [dimensionless]
$AC_1$	= high clouds at sunrise [oktas]
$AC_2$	= high clouds at noon [oktas]
$A_{hru}$	= area of the hydrologic response unit [ha]
$AVC_{ly}$	= available water capacity for layer $ly$ [mm of H <sub>2</sub> O]
$b$	= an empirically determine regression coefficient [s/m <sup>2</sup> ]
$b$	= empirical coefficient [dimensionless]
$C$	= crop management factor [dimensionless]
$C$	= runoff coefficient [dimensionless]
$C_0$	= fixed cost of production per unit area [\$/ha]
$C_1$	= costs of production varying with crop yield [\$/ha]
$C_2$	= cost of irrigation water [\$/m <sup>3</sup> ]
$C_3$	= cost of distributing irrigation water [\$/ha]
$C_4$	= fixed cost of each irrigation [\$(event·ha)]
$C_{ID}$	= irrigation installation net annual depreciation [\$/ha]
$CLAY$	= clay content [dimensionless]
$CN$	= curve number representing runoff potential for a soil cover complex (values 2 to 100)
$C_{NO3,m}$	= concentration of nitrate in the mobile water for a given layer [kg N/mm H <sub>2</sub> O]
$C_p$	= agricultural cost of production [\$/ha·yr]
$c_p$	= specific heat of moist air at constant pressure [MJ/kg·°C] ( $1.01 \times 10^{-3}$ MJ/kg·°C)
$c_s$	= general heat conductance for the soil surface [approx. 0.38 MJ/m <sup>2</sup> ·day·°C]
$C_w$	= cost of water per unit volume [\$/m <sup>3</sup> ]
$d_h$	= zero plane displacement height [m]
$D$	= current calendar day of the year [day]
$d$	= day of the growing season [day]
$D_c$	= date of effective full cover [day]
$DP$	= deep percolation [mm]
$D_p$	= planting date [day]
$DP_i$	= deep percolation on day $i$ [mm]
$d_r$	= relative distance of the earth from the sun
$d_{surf}$	= depth of the surface layer [10 mm]
$e_a$	= actual vapor pressure [kPa]
$E_c$	= water use efficiency [kg/ha·mm]
$e_d$	= saturation vapor pressure at dew point temperature [kPa]
$EFI$	= total irrigation efficiency [dimensionless]
$epco$	= plant uptake compensation factor
$ERF_t$	= effective rainfall at time = $t$ [mm/hr]

$e_s$	= saturation vapor pressure [kPa]
$e_s - e_a$	= vapor pressure deficit [kPa]
$ET_0$	= reference evapotranspiration [mm]
$ET_{0r}$	= reference evapotranspiration rate [mm/day]
$ET_a$	= actual evapotranspiration [mm]
$ET_{a i}$	= actual crop evapotranspiration on day $i$ [mm]
$ET_i$	= evapotranspiration on day $i$ [mm of water]
$ET_m$	= maximum evapotranspiration for the specific plant species [mm]
$ET_p$	= potential evapotranspiration [mm]
$ET_t$	= target evapotranspiration [mm]
$F_a$	= plotting position [%]
$F_c$	= fixed cost of crop production [\$/ha]
$FC$	= water content in soil profile at field capacity [mm]
$FC_{ly}$	= water content of the soil layer at field capacity [mm H <sub>2</sub> O]
$fr_{LAI,1}$	= fraction of the maximum plant leaf area index corresponding to the 1 <sup>st</sup> point on the optimal leaf area development curve [dimensionless]
$fr_{LAI,2}$	= fraction of the maximum plant leaf area index corresponding to the 2 <sup>nd</sup> point on the optimal leaf area development curve [dimensionless]
$fr_{LAI_{mx}}$	= fraction of the plant's maximum leaf area index corresponding to a given fraction of potential heat units, given by equation 42 [dimensionless]
$fr_{PHU}$	= fraction of potential heat units accumulated for the plant on a given day in the growing season [dimensionless]
$fr_{PHU,1}$	= fraction of the growing season corresponding to the 1 <sup>st</sup> point on the optimal leaf area development curve [dimensionless]
$fr_{PHU,2}$	= fraction of the growing season corresponding to the 2 <sup>nd</sup> point on the optimal leaf area development curve [dimensionless]
$fr_{r_{max}}$	= fraction of the maximum stomatal conductance [dimensionless]
$fr_{root}$	= fraction of the total biomass of the roots on a given day
$g$	= gravitational constant [9.81 m/s <sup>2</sup> ]
$G$	= soil heat flux [MJ/m <sup>2</sup> ·day]
$G_c$	= groundwater contribution [mm]
$G_{sc}$	= solar constant [MJ/m <sup>2</sup> ·min] (0.08202 MJ/m <sup>2</sup> ·min)
$GW_i$	= upward flux of water from a shallow water table on day $i$ [mm]
$H$	= hydraulic head [cm]
$H_0$	= saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness [mm/mm]
$h_c$	= canopy height for a given day [m]
$h_c$	= mean height of vegetative canopy [m]
$h_{c,mx}$	= plant's maximum canopy height [m]
$H_{day}$	= incident total solar radiation [MJ/m <sup>2</sup> ]
$H_{phosyn}$	= intercepted photosynthetically active radiation [MJ/m <sup>2</sup> ]
$HRU$	= Hydrologic Response Unit (abbreviation), defined in the SWAT model as a unique land cover and soil type
$HU$	= heat units accumulated on day $i$ [heat units]
$I$	= crop water requirement [\$/ha]
$i$	= rainfall intensity [mm/hr]

$i$	= (as subscript) month of the year (January – December) [month number]
$I_a$	= initial abstraction [mm]
$I_{Ann}$	= annual irrigation water demand for watershed [m <sup>3</sup> ]
$I_D$	= effective minimum irrigation depth applied [mm]
$I_{FL}$	= final irrigation soil water level [mm]
$I_{IP}$	= fraction of total plant available soil water at the irrigation intervention point [dimensionless]
$Irr_I$	= irrigation interval between irrigation events [days]
$I_{n\ i}$	= net irrigation depth on day $i$ [mm]
$I_r$	= irrigation water depth applied [mm]
$j$	= (as subscript) HRU contained within subbasin $k$ [number]
$K$	= soil erodibility factor [dimensionless]
$k$	= von Karmans' constant for turbulent diffusion (0.41)
$k$	= (as subscript) subbasin contained within the overall watershed [number]
$K_c$	= crop coefficient [dimensionless]
$k_{d,surf}$	= phosphorus soil partitioning coefficient [m <sup>3</sup> /Mg]
$k_l$	= light extinction coefficient
$KN$	= empirically determined constant for crop variety [dimensionless]
$K_{sat}$	= saturated hydraulic conductivity [mm/h]
$k_y$	= a crop yield response factor [dimensionless]
$l_1$	= shape coefficients [dimensionless]
$l_2$	= shape coefficients [dimensionless]
$LAI$	= the active or sunlit leaf area index [m <sup>2</sup> (leaf area)/ m <sup>2</sup> (soil surface)]
$LC_1$	= low clouds at sunrise [oktas]
$LC_2$	= low clouds at noon [oktas]
$L_{hill}$	= hillslope length [m]
$L_{hill}$	= hillslope length [m]
$LS$	= slope length and steepness factor [dimensionless]
$LQ$	= lateral flow during time step [mm]
$m$	= CROPWAT variable ranking number [integer]
$m$	= number of HRU's within the subbasin that contain agricultural crops [number]
$m_c$	= percent clay content [%]
$n$	= number of subbasins within the overall watershed that contains agricultural crops [number]
$N$	= number of records in CROPWAT model [integer]
$N_a$	= required nitrogen application [kg/ha]
$NB$	= net benefit per unit area [\$/ha]
$NB_I$	= net benefit with irrigation [\$/ha]
$NO3_{ly}$	= amount of nitrate in the layer [kg N/ha]
$N_w$	= number of irrigation application events [dimensionless]
$P$	= erosion control practice factor [dimensionless]
$p$	= the soil water depletion fraction for no stress [mm/mm]
$P_0$	= known atmospheric pressure [kPa]
$P_I$	= desired pressure estimate at elevation [kPa]
$P_a$	= atmospheric pressure [kPa]

$P_c$	= unit price received for the crop [\$/kg]
$P_e$	= effective precipitation [mm]
$PERC$	= percolation past the root zone during time step [mm]
$PHU$	= total potential heat units for the plant [heat units]
$P_i$	= precipitation on day $i$ [mm]
$PkW$	= power output [kW]
$PRECIP$	= amount of precipitation falling during time step [mm]
$P_r$	= pumping rate or discharge [L/sec]
$P_s$	= sale price of yield [ton/ha]
$P_{sol,surf}$	= phosphorus in solution in the top 10 mm [kg P/ha]
$P_{surf}$	= soluble phosphorus lost in surface runoff [kg P/ha]
$P_w$	= cost of water [\$/m <sup>3</sup> ]
$Q$	= direct runoff [mm]
$Q_a$	= applied water [m <sup>3</sup> /hectare]
$Q_i$	= surface runoff on day $i$ [mm]
$q_p$	= peak runoff coefficient (values 0.02 to 0.95)
$Q_p$	= peak runoff rate [m <sup>3</sup> /s]
$Q_{r,i}$	= runoff from the soil surface on day $i$ [mm]
$QR_i$	= return flow on day $i$ [mm of water]
$Q_{surf}$	= amount of surface runoff on a given day [mm]
$Q_{surf}$	= surface runoff [mm]
$R$	= available water depth [mm]
$r_l$	= average minimum daytime value of stomatal resistance for a well illuminated leaf [s/m]
$r_a$	= aerodynamic resistance to vapor and heat diffusion [s/m]
$R_a$	= extraterrestrial radiation [MJ/m <sup>2</sup> ·day]
$R_c$	= specific gas constant [286.9 J/kg·K]
$R_D$	= depth of root zone [mm]
$R_{day}$	= accumulated rainfall [mm of water]
$RVAP$	= return water from shallow aquifer to the root zone [mm]
$R_{max}$	= upper limit of <i>optimal yield zone</i> [mm]
$R_{min}$	= lower limit of <i>optimal zone</i> /upper limit of <i>water stress zone</i> [mm]
$R_n$	= net radiation [MJ/m <sup>2</sup> ·day]
$r_p$	= flow resistance in plant pathway [dimensionless]
$r_s$	= bulk stomatal or canopy resistance [s/m]
$r_{sr}$	= flow resistance in soil pathway [dimensionless]
$R_s$	= measured short wave global radiation [MJ/m <sup>2</sup> ·day]
$R_{so}$	= clear sky short wave global radiation (i.e. no clouds) [MJ/m <sup>2</sup> ·day]
$R_{nl}$	= outgoing net longwave radiation [MJ/m <sup>2</sup> ·day]
$R_{ns}$	= incoming net shortwave radiation [MJ/m <sup>2</sup> ·day]
$R_{z_i}$	= initial effective rooting depth at planting or plant emergence [m]
$R_{z_{max}}$	= maximum effective rooting depth for a mature crop [m]
$RUE$	= radiation-use efficiency [(kg/ha)/( MJ/m <sup>2</sup> )]
$SAT_{ly}$	= amount of water in the soil layer when saturated [mm H <sub>2</sub> O]
$SF$	= snowfall during time step [mm of water]
$slp$	= slope input, increase in elevation per unit distance [m/m]

$SM$	= snowmelt during time step [mm of water]
$SOL\_BD$	= bulk density [ $Mg/m^3$ ]
$SOL\_AWC$	= total plant available soil water [mm/mm]
$SOL\_AWC_{ly}$	= available plant water content for soil layer [mm]
$SOL\_Z$	= depth from soil surface to bottom of soil layer [mm]
$S_r$	= potential difference between rainfall and direct runoff [mm]
$SSP$	= sunshine [%]
$SQ$	= surface runoff during time step [mm]
$SW$	= average soil-water content without irrigation [mm]
$SW_{ly}$	= soil water of soil layer [mm $H_2O$ ]
$SW_{ly,excess}$	= drainable volume of water of soil layer [mm $H_2O$ ]
$T$	= temperature [ $^{\circ}C$ ]
$T$	= temperature [K]
$t$	= time [days]
$T$	= transpiration [cm]
$T'_v$	= virtual temperature [K]
$T_0$	= absolute temperature [K]
$T_a$	= average daily temperature [ $^{\circ}C$ ]
$T_{dew}$	= dewpoint temperature [ $^{\circ}C$ ]
$tdh$	= total dynamic head [m]
$T_{maxK}$	= maximum daily air temperature [K]
$T_{minK}$	= minimum daily air temperature [K]
$T_p$	= average daily temperature for past three days [ $^{\circ}C$ ]
$t_s$	= time step [days]
$TT_{perc}$	= travel time for percolation [hrs]
$U$	= usable soil water capacity [mm]
$u_z$	= wind speed at height $z$ [m/s]
$u$	= wind speed at 2 m height [m/s]
$v$	= specific volume of water [ $cm^3/g$ ]
$V$	= surface runoff volume [ $m^3$ ]
$V_a$	= net available irrigation volume per unit area [ $m^3/ha$ ]
$V_c$	= variable cost in producing crop [\$/kg]
$V_{HRU}$	= annual irrigation water demand for individual HRU [ $m^3$ ]
$V_{SUB}$	= annual irrigation water demand for a subbasin [ $m^3$ ]
$V_{WAT}$	= annual irrigation water demand for overall watershed [ $m^3$ ]
$V_I$	= volume of irrigation water per irrigation event [ $m^3$ ]
$Vol_I$	= total volume of irrigation applied per unit area over time step [ $m^3/ha$ ]
$V_z$	= water stored in lower layer of thickness $z$ , which is explored by roots after equivalent root growth [mm]
$w_{actualup}$	= total actual water uptake [mm of $H_2O$ ]
$w_{actualup,ly}$	= actual water uptake for soil layer [mm of $H_2O$ ]
$w_{demand}$	= water uptake demand not meet by overlaying layer [mm of $H_2O$ ]
$w_{mobile}$	= amount of mobile water in layer [mm of water]
$w_{perc,ly}$	= amount of water percolating to the underlying soil layer [mm of water]
$WP_{ly}$	= water content at wilting point [mm/mm]
$wstrs$	= water stress for the given day [dimensionless]

$w_{up,ly}$	= potential water uptake for soil layer [mm of H <sub>2</sub> O]
$w_{up,z}$	= potential water uptake from the soil profile at a specified depth $z$ [mm of H <sub>2</sub> O]
$w_{up,zl}$	= potential water uptake for lower boundary [mm of H <sub>2</sub> O]
$w_{up,zu}$	= potential water uptake for upper boundary [mm of H <sub>2</sub> O]
$w'_{up,ly}$	= adjusted potential water uptake for soil layer [mm of H <sub>2</sub> O]
$w''_{up,ly}$	= potential water uptake adjusted for initial soil water content [mm of H <sub>2</sub> O]
$Y$	= crop yield [kg/ha]
$YLD$	= harvested yield without supplemental irrigation [tons/ha]
$Y_a$	= actual crop yield [ton/ha]
$Y_I$	= expected yield with supplemental irrigation [tons/ha]
$Y_{ield}$	= sediment yield from subwatershed (metric tons)
$Y_m$	= maximum crop yield [kg/ha]
$Y_t$	= target yield with supplemental irrigation [tons/ha]
$z$	= depth from the soil surface [mm]
$z_h$	= height of humidity measurements [m]
$z_m$	= height of wind measurements [m]
$z_{oh}$	= roughness length governing transfer of heat and vapor [m]
$z_{om}$	= roughness length governing momentum transfer [m]
$z_{r i}$	= root depth on day $i$ [m]
$z_r$	= root depth of crop [mm]
$z_{root}$	= root development in the soil on a given day [mm]
$z_{root,max}$	= maximum depth for root development in the soil [mm]
$\alpha$	= albedo (0.23 for hypothetical reference lawn) [dimensionless]
$\alpha$	= assumed constant adiabatic lapse rate [K/m]
$\alpha$	= empirical parameter ( $\approx 0.3$ ) [dimensionless]
$\beta_w$	= water use distribution parameter [dimensionless]
$\gamma$	= psychrometric constant [kPa/°C]
$\delta$	= declination of the sun [radians]
$\Delta$	= slope of the saturation vapor pressure-temperature relationship [kPa/°C]
$\Delta bio$	= potential increase in plant biomass on a given day [kg/ha]
$\Delta h$	= elevation above datum [m]
$\Delta p$	= hydrostatic pressure in excess of atmospheric pressure [kPa]
$\Delta R$	= soil water variation during interval $\Delta t$ [mm·hr]
$\Delta t$	= time interval [hr]
$\Delta t_s$	= length of time step [hr]
$\varepsilon$	= ratio of molecular weights of air to water (0.622)
$\theta_0$	= initial soil water content available for plant uptake on day $i$ , defined as the initial soil water content minus the permanent wilting point water content [mm H <sub>2</sub> O]
$\theta_e$	= fraction of porosity from which anions are excluded [dimensionless]
$\theta_f$	= final soil water content [mm H <sub>2</sub> O]
$\theta_{FC}$	= soil water content at field capacity [mm/mm]
$\theta_i$	= average soil water content in the root zone [mm/mm] on day $i$
$\theta_{i-1}$	= soil water content on the previous day [mm/mm]
$\theta_{ly,excess}$	= drainable volume of water on a given day [mm H <sub>2</sub> O]

$\theta_{s,ly}$	= saturated water content of the soil layer [mm]
$\theta_t$	= soil water content at time = $t$ [mm]
$\theta_{t-1}$	= soil water content at time = $t-1$ [mm]
$\theta_{WP}$	= soil water content at wilting point [mm/mm]
$\lambda$	= latent heat of vaporization [MJ/kg]
$\lambda ET_0$	= vapor flux density [MJ/m <sup>2</sup> ·day]
$\rho_a$	= atmospheric density [kg/m <sup>3</sup> ]
$\rho_b$	= bulk density of the top 10 mm [Mg/m <sup>3</sup> ]
$\rho_{b,ly}$	= bulk density for soil layer [Mg/m <sup>3</sup> ]
$\rho_s$	= particle density [Mg/m <sup>3</sup> ]
$\rho_w$	= density of water [kg/m <sup>3</sup> ]
$\sigma$	= Stephan-Boltzman constant ( $4.903 \times 10^{-9}$ MJ/m <sup>2</sup> ·day·K)
$\phi$	= latitude of the station [radians]
$\Phi_d$	= drainable porosity of the soil [mm/mm]
$\Psi_a$	= adsorption potential [cm]
$\Psi_c$	= capillary potential [cm]
$\Psi_g$	= gravitational potential [cm]
$\Psi_m$	= matric potential [cm]
$\Psi_o$	= osmotic potential [cm]
$\Psi_p$	= pressure potential [cm]
$\Psi_{plant}$	= total plant water potential [cm]
$\Psi_{soil}$	= total soil water potential [cm]
$\Psi_w$	= molecular attraction potential [cm]
$vfr_{max}$	= vapor pressure deficit corresponding to $fr_{max}$
$\omega_s$	= sunset hour angle [radians]

## **CHAPTER I. INTRODUCTION:**

Irrigation technology is inextricably interwoven with agriculture production in arid regions, but has not found wide spread use in more temperate humid regions, due primarily to a lack of concrete justification for the steep capital costs associated with irrigation installation and practice. Nevertheless, irrigation remains the only means by which water requirements can be met during periods of reduced precipitation or drought conditions. In humid regions irrigation technology serves as a safeguard, ensuring continued high yields during drought conditions, which could potentially be devastating to farmers.

The aim of this project is to develop a tool to consider irrigation installations and associated water demand on a watershed or sub-watershed scale to identify parcels of land that could best be served by supplemental irrigation based on land use, crop type, soil type, soil layer depths, water holding capacity, surface and subsurface flow, and prevailing meteorological conditions, all of which can vary significantly over a given region. Water movement and accumulation through the environment is complex process and varies greatly throughout the landscape. Hydrological patterns could potentially lead to areas where water is plentiful and scarce within a given terrain. As a result these factors can lead to highly variant irrigation requirements even within the same climatic zone or geographical region.

Several irrigation scheduling programs have been produced that aim at aiding farm managers and irrigation engineers to determine and design for their irrigation needs, for a given crop-field combination. A few commonly used irrigation programs include:



CROPWAT (Smith, 1992), ISAREG (Pereira et al., 2003), SCHED (Harrington & Heermann, 1981) and WATSCHED (Howard & Ben, 1986). However, none of these programs are designed to look at the highly variant conditions found over a given watershed or terrain, and simultaneously identify the potential net benefit of irrigation for each area, thereby prescribing priority use for limited water resources. In addition, these programs do not provide insight into the environmental impact that irrigation may have on a given area, in terms of non-point source pollution and potential water demand.

An invaluable tool, in any spatially oriented project of this scale, is a complex geospatial data processing system commonly referred to as a geographical information system (GIS). Graphical information systems currently allow users to integrate and reference a wide range of data over a highly diversified spatial terrain, and to apply user developed models and expert systems to the assembled spatial database. Such a system, in combination with an irrigation model, can be potentially used to identify parcels of land that offer the highest economic return if an irrigation system is available. Using the same model, water resource managers can estimate the total agricultural water demand over a given watershed based on optimal irrigation-schedules produced for parcels of agricultural land known to have irrigation systems installed or which could potentially profit from the installation of an irrigation system.

Currently, several watershed scale hydrologic models exist, such as the Soil Water Assessment Tool (SWAT) (Neitsch et al., 2002a), the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) model (EPA, 2004a), and the MIKE-SHE model (Kalin & Hantush, 2003), that can be used in conjunction with GIS data. Each model is capable of estimating surface and subsurface flow over a given watershed

based on meteorological and land properties data supplied. A hydrological model combined with GIS can be used to simulate water movement and availability over a wide range of conditions. This information can then be supplied to the irrigation model to determine if irrigation is recommended for multiple parcels of land, and to integrate this information into a complete hydrological model. Once developed, a decision support system or expert system can be applied to identify those regions of greatest need for supplemental irrigation, based on predicted increases in crop yield and profitability. In addition, the system can assist in identifying the irrigation system, given an array of potential systems, that may be best suited for a given region based on economic return, water use efficiency and application method.

Such an integrated approach will allow natural resource managers, policy makers and large landowners to predict projected water needs, and to identify areas where the installation of supplemental irrigation systems are justified. Such a tool would be useful in estimating the expected economic return of the irrigation water supplied, and the environmental impact, in terms of both water demand and water quality, that such a use may have on surface and subsurface water sources.

The benefit of taking an integrated approach to irrigation analysis over a watershed scale lies in the ability of the hydrological model to identify parcels of land or fields that may benefit most from supplemental irrigation. Over a heterogeneous terrain landscape conditions vary considerably, thus resulting in areas of higher and lower soil-water holding capacity. Moreover, surface runoff or subsurface flow from one field to the next, may result in the accumulation of water in certain fields, and the subsequent draining of others. Taking a macro level approach to irrigation application allows one to

identify areas of greatest need and allocate limited resources. The approach also aids in the determination of the effects of natural conditions and water management practices occurring on adjacent fields. This sort of approach has benefits both on a macro watershed scale and on a micro farm site scale, where heterogeneous conditions and practices may have an impact on irrigation water requirements.

The primary aim of this project is to develop such a model and to apply it to the Pocomoke watershed located on Maryland's eastern shore. Maryland has historically enjoyed sufficient rain to meet its water needs, and therefore, has not had the need to rely upon intense irrigation to ensure agricultural productivity. However, seasonal fluctuations in rainfall levels do cause periodic reductions in yield due to water stress during years of reduced precipitation or drought conditions, and yet the majority of the agricultural land in production is not equipped for supplemental irrigation.

The application developed in this project is used to identify fields most likely to profit from irrigation installations and the associated water application. This tool may allow planners and resource managers to look at the long-term development of agriculture in Maryland and its effects on water resources. It may also be used by governmental agencies and private investors to justify the substantial capital cost associated with irrigation installations, and thereby, more intelligently evaluating the economic risks involved.

Moreover, despite the plentiful rains that Maryland has enjoyed, there is increasing concern about the long-term sustainability of water resources and environmental degradation in light of decreasing water table levels throughout the state (Wolman, 2004). At one level, advocating the use of irrigation technology may appear to

lead to an added drain on the state's water resources. However, the modeling tool developed in the study will allow water resource managers and policy makers to have a better grasp of what are the state's optimal agricultural water needs, and more importantly what is the added economic value of the use of water resources for agricultural production. This sort of information is indispensable to policy makers and planners. The model will aid farm managers in determining the expected minimum or most effective amount of water to be applied, through the prescription of proper irrigation scheduling procedures that makes the most efficient use of irrigation technology. Following strict and carefully formulated irrigation scheduling practices will lead to higher yield returns with lower water waste and inefficiency. Further use and development of the model could lead to the prescription of more efficient irrigation technologies with higher distribution efficiency, based on the total economic return. In such a context, proper irrigation application remains one of the most effective tools for the conservation and intelligent allocation of limited water resource (Fereres, 1996).

Addressing the rising concern over the effects of non-point source pollution from agricultural production facilities, effective supplemental irrigation may in fact reduce nutrients from leaving the agricultural site by ensuring maximum utilization of agricultural inputs. Agriculture involves a substantial input of fertilizers and agrochemicals that contribute to the total productivity of the fields. However, excess fertilizers and agrochemicals not utilized by crop species find their way into rivers and streams through direct runoff and subsurface leaching during periods of high precipitation (Shirmohammadi and Knisel, 1994), leading to the rapid cultural eutrophication of natural water systems. Irrigation may allow for higher, more consistent

and predictable crop growth rates, although supporting research has not been undertaken. By reducing the variability associated with crop growth rates, from year to year, higher fertilizer efficiencies can be achieved.

During drought years crop growth is reduced, resulting in lower than expected yields and the under utilization of fertilizer inputs, leaving a greater quantity of nutrient inputs within the soil profile. This excess fertilizer is then transported into local bodies of water once precipitation does occur. This process can be somewhat alleviated by ensuring uniform plant growth rates under well-watered conditions during both drought and non-drought years, which leads to maximum utilization of fertilizer inputs, assuming that conservative irrigation management strategies are in place that do not lead to runoff and excessive leaching.

## **CHAPTER II: LITERATURE REVIEW:**

### **Global and Local Perspectives:**

#### *Global Perspective:*

The Consultative Group on International Agricultural Research (CGIAR), a research review agency created by the World Bank in 1971, warns that as the 21<sup>st</sup> century begins the world will face another food crisis just as severe, although far more complex, as the food shortage confronted 30 years ago that sparked the 'Green Revolution.' (Shah and Strong, 2000). It is estimated that the world's population climbs by 90 million people each year, meaning the world's farmers will have to increase production by at least 50% by the year 2020, and possibly as much as 100%, if the current trends in increased meat consumption continue, requiring higher quantities of feed grains.

The Green Revolution that averted the catastrophic famines and global food shortages expected by the world's experts in the 1960's succeeded as a result of a concerted effort of a multitude of factors, including, an increase in high-yield food crop varieties, an increase in crop lands, the extensive use of fertilizers and irrigation, and more intensive fisheries (Shah and Strong, 2000). However, the current challenge of increasing food production is more complex than it had been in the past for a number of reasons. In contrast with the world's potential for agricultural expansion found 30 years ago, increases in today's food production appear to be peaking, environmental impacts have taken on new importance with regards to land use and nutrient management, the most promising lands are already under cultivation, the world's fisheries are overexploited, and increasing water shortages are being seen throughout the world (Shah

and Strong, 2000). All of these factors present new challenges and limit the potential for increasing food production throughout the world.

Of all of these factors, water scarcity is potentially the most serious obstacle to ‘food security, poverty reduction and protection of the environment’ and is likely to affect one-quarter of the world’s population within the next 25 years (Shah and Strong, 2000). Currently about 80% of the world’s freshwater supply goes to agriculture, a number that will inevitably rise if the world is to meet its’ ever increasing food demand, thereby increasing the so called ‘world water gap,’ as groundwater levels are falling world wide (CGIAR, 1998). These factors underscore the imperative for ‘more crop for every drop,’ the new mantra for the world’s agricultural industry. The current challenge of the world is to then increase food production with more efficient and well-managed use of input resources, particularly of water resources.

*Irrigation in the United States and Maryland:*

On a local level, Maryland agriculture enjoys consistent rains throughout the year, capable of meeting its present needs. However, the ever increasing water thirsty population and potential supply shortages suffered by some communities in the wake of the 1999-2002 drought has ignited concern for the adequacy of the state’s water supply resources (Wolman et al., 2004). As a result, statewide attention has been drawn to the steady decline of water levels, particularly in the southern Maryland aquifers.

Freshwater use by agriculture for irrigation, livestock and aquaculture, accounts for a relatively small portion of the state’s freshwater demand, varying between 3% and 5% over the past 25 years (Wolman et al., 2004). Nevertheless, agricultural water withdrawals are often concentrated in specific regions where agricultural production is

particularly intense. Current data shows that 80% of the states agricultural water withdrawals occur within the eastern shore (Wolman et al., 2004) where agricultural demand can significantly impact water availability.

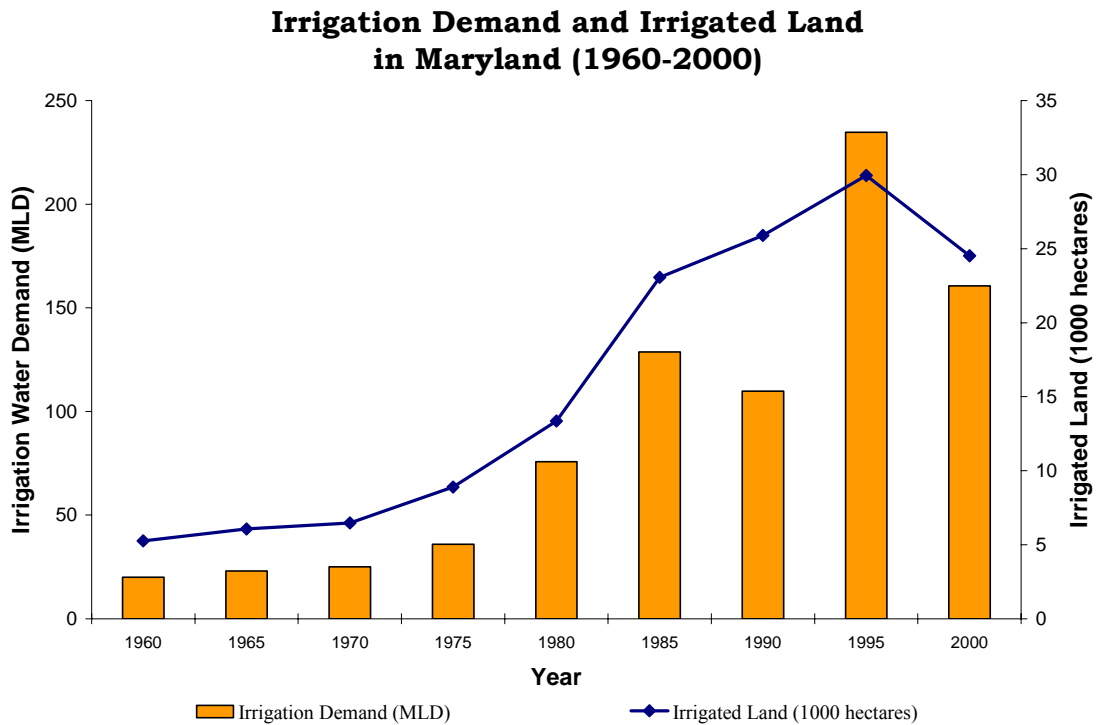
The problem is exacerbated when we consider that agricultural demand is highest during periods of low precipitation or drought conditions, when aquifer levels are at their lowest. Therefore, it is critical that conservative irrigation practices be implemented in order to protect the states water resources. This may be accomplished by increasing irrigation efficiencies due to improvements in irrigation technology and implementation, as well as improvements in irrigation management practices through proper scheduling, and the use of a decision support system to determine the minimum required irrigation for maximum yield.

Maryland has, for the most part, not had to rely upon supplemental irrigation to meet its crop water needs. Currently only 6% of all agricultural land in Maryland is equipped with supplemental irrigation systems (Wolman et al., 2004), while the remaining 94% of agricultural lands rely upon precipitation alone to meet their water needs.

However, historical evidence suggests that the use of irrigation systems, within temperate zones, is likely to increase in the future, as the agricultural industry attempts to maximize production by equipping croplands with irrigation infrastructure, and as irrigation technology and management strategies become more effective. Figure 1 shows the rapid growth of both the irrigation water demand and the total acreage of irrigated agricultural land within Maryland.



The data presented in Figure 1 is obtained from a series of circular reports produced by the USGS detailing the estimated use of water from the years 1960 to 2000, published in 5 year intervals. The agricultural water demand in Maryland increased from an average of 18.9 liters per day (LPD) (5 million gallons per day (MGD)) in 1960 to as much as 235 LPD (62 MGD) in the mid-1990's, while the quantity of irrigated land increased from as little as 5,250 hectares (13,000 acres) in 1960 to over 24,300 hectares (60,000 acres) in the year 2000.



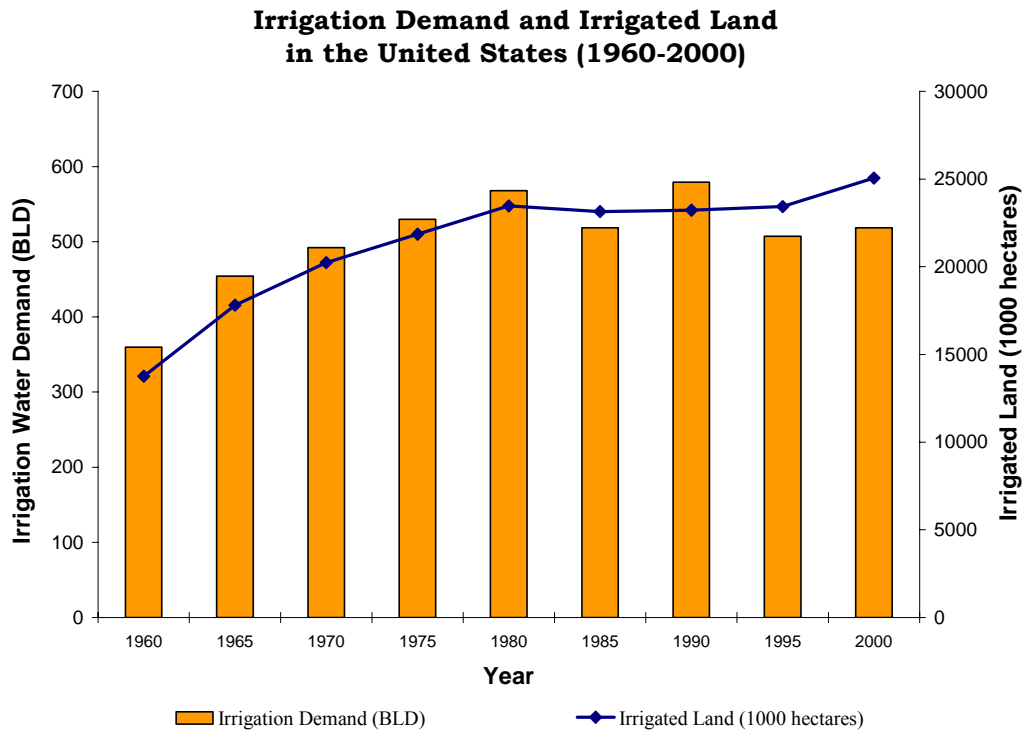
**Figure 1.** Growth of irrigation water demand and irrigated agricultural land in Maryland from the year 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

The data indicates a dramatic rise in both the quantity of irrigated land and the volume of irrigation water demand. An eight fold increase in irrigated land is observed over the 40 year period, with irrigation water demand following this general trend. The

overall annual irrigation water demand in temperate zones is dependent upon yearly precipitation rates and prevailing irrigation management strategies, and therefore is variable and less predictable from year to year; although the overall trend shows a clear increase in the irrigation water demand.

On a national level a parallel increase in irrigated land is observed, while the associated increase in irrigation water demand has been offset, in recent years, due to the replacement of older less efficient irrigation systems with more efficient systems. According to the USGS (Hutson et al., 2004), the total number of irrigated acres more than doubled, over a 30 year period, from 10,100,000 hectares (25,000,000 acres) in 1950 to 23,500,000 hectares (58,000,000 acres) in 1980. Between the years 1980 to 2000 the total number of irrigated acres remained relatively constant, increasing to just over 25,000,000 hectares (61,900,000 acres) by the year 2000 (as shown in Figure 2) in response to drought conditions suffered in many parts of the United States including Maryland. The rapid increase in irrigated land in the 1960's and 1970's is attributed to the rise of irrigation technology and the expansion of irrigation in western states.

The more dramatic and relatively recent rise in irrigated agricultural land in Maryland, over the past 30 years, may be the result of the expansion of sprinkler irrigation systems, as well as changes in the hydrologic pattern associated with various regions. A significant portion of the arid flat agricultural regions of the mid-west had already been equipped with some form of surface irrigation prior to 1960 and therefore a less dramatic rise in irrigated land is observe on a national level. Figure 2 below presents the quantity of irrigated land in the United States and the associated irrigation water demand from the years 1960 to 2000.



**Figure 2.** Growth of irrigation water demand and irrigated agricultural land in the United States from the year 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

Nationally, as a general trend, the rise in irrigation water demand is offset by the implementation of more efficient sprinkler and drip irrigation systems, in place of the less efficient and more wasteful flood and surface irrigation practices. The irrigation water demand in the United States increased from 337 to 570 billion liters per day (89 to 150 billion gallons per day) from 1950 to 1980 as a result of the expansion of irrigation throughout the United States. However, the irrigation water demand has since that time stabilized between 507 and 519 billion liters per day (134 and 137 billion gallons per day), between the years 1985 to 2000, despite moderate increases in the total number of acres irrigated (Hutson et al., 2004). This decline in irrigation water demand is attributed to the replacement of flood and surface irrigation systems with more efficient sprinkler

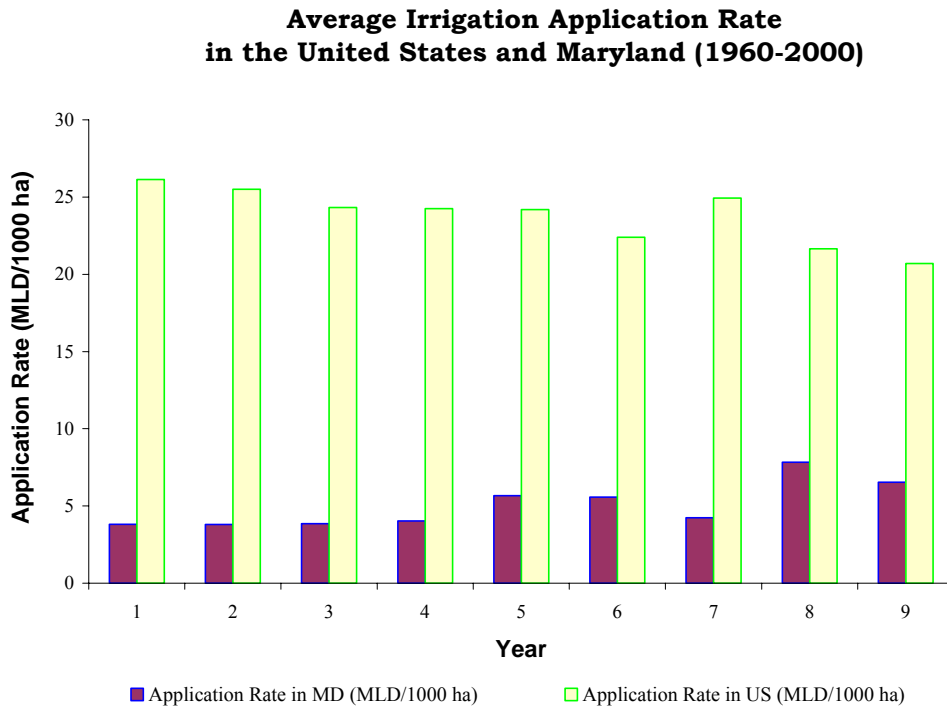
and micro-irrigation systems. A trend that is likely to continue as greater demands are placed on limited water supplies throughout the country. In 1985 the portion of agricultural land equipped with sprinkler and micro-irrigation systems constituted less than 40% of the total irrigated acreage; this portion increased to 52% in the year 2000 resulting in an overall decline in the average irrigation application rate (Hutson et al., 2004), as observed in Figure 2.

In contrast, a similar decline since the 1980's in the irrigation water demand is not observed in Maryland; rather irrigation water demand has continued to increase with the expansion of irrigated land. This is due largely to the fact that the expansion of irrigation in Maryland is the result of the installation of new sprinkler irrigation systems in previously non-irrigated land, rather than the replacement of less efficient surface irrigation systems as observed in other parts of the country.

The USGS reports that as of 1985 all irrigated land in Maryland was supplied by sprinkler irrigation (Solley et al., 1988). The use of micro and drip irrigation systems for agricultural production in Maryland were first recorded in USGS estimated water use circular reports in the year 2000, and represented only a small portion of the total irrigated land (approximately 5%).

Therefore, as observed on the national level, if the rise in irrigation water demand is to be curbed in Maryland, the migration from less efficient irrigation systems to more efficient systems will have to be encouraged. Therefore, the effective implementation of more efficient systems, coupled with stringent water conservation practices, will be necessary if Maryland is to meet the growing water demand, while balancing the need for increasing agricultural production.

Figure 3 below presents the application rate in MLD per 1000 hectares of irrigated land on a national and statewide level. Lower application rates indicate the use of more efficient irrigation systems, while higher application rates reflect a more predominate use of less efficient flood and surface irrigation techniques.



**Figure 3.** Average irrigation application rate in the United States and statewide within Maryland from the year 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

On a national level a steady decline in the average irrigation application rate is observed, while locally within Maryland irrigation application appears to be increasing, and yet remains far below the national average due to both the temperate climate and the predominate use of sprinkler irrigation, on a supplemental basis, as opposed to surface irrigation used in other parts of the country. On a national level, according to the USGS, as of the year 2000, surface or flood irrigation systems remained the dominate form of

irrigation for the majority of irrigated land. In the year 2000 an estimated 119,000,000 hectares (294,000,000 acres) were irrigated by surface irrigation compared to 114,500,000 and 1,690,000 hectares (283,000,000 and 4,180,000 acres) being irrigated by sprinkler or drip irrigation, respectively. As the percentage of irrigated land begins to shift toward more efficient irrigation systems the average irrigation application rate is likely to continue to fall.

The national trend of increasing irrigated land while maintaining a steady or declining irrigation water supply indicates that it is possible to accommodate additional irrigated acreage without increasing the total water demand. However, this trend is not observed within Maryland, which according to the USGS, has relied almost exclusively on sprinkler irrigation throughout the 40 year period. Therefore, if the average irrigation application rate is to be improved a greater percentage of micro and drip irrigation will have to be utilized.

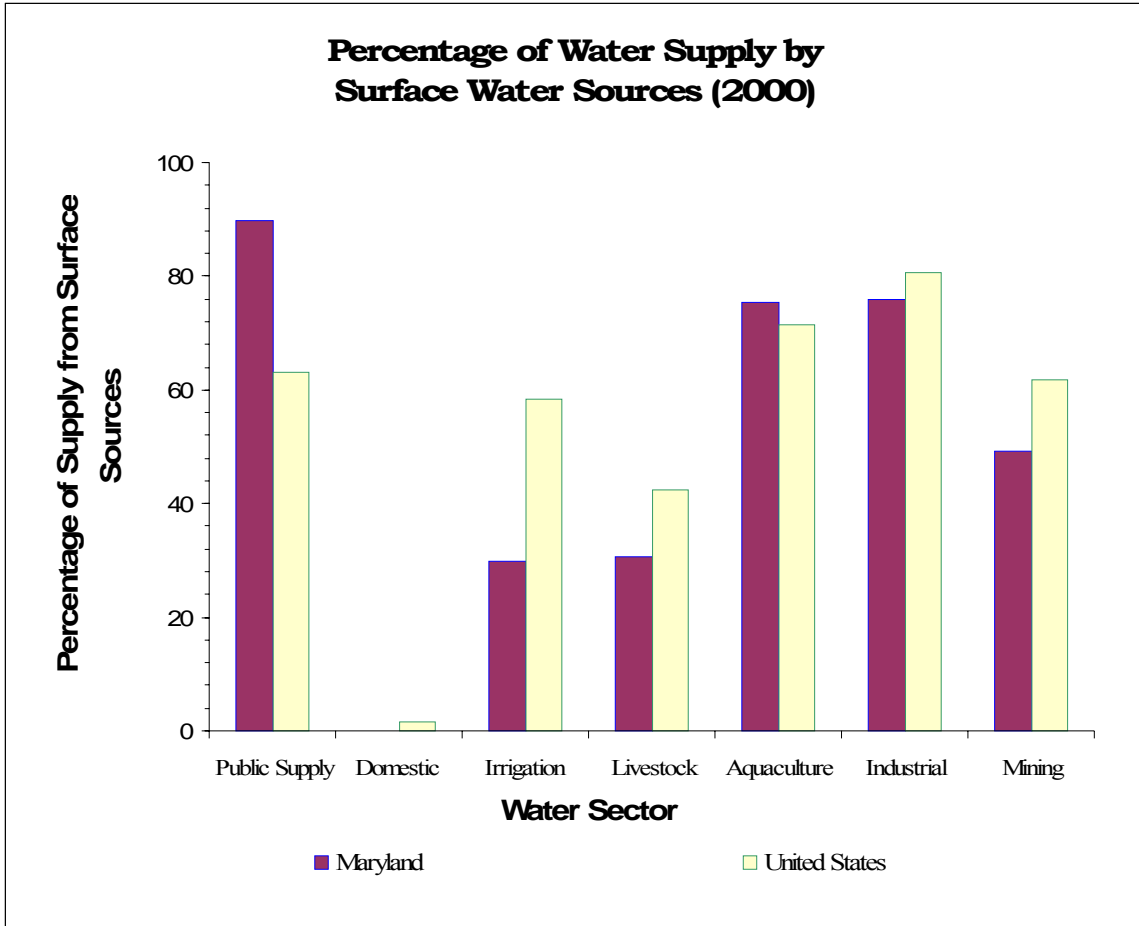
The apparent rise in application rate may be the result of a number of factors including: the increased production of more water thirsty crop varieties, changes in precipitation and climatic variables between documented years, and greater dependence upon or the more extensive use of permanent sprinkler irrigation systems in place of less frequent irrigation events associated with traveling gun systems. Unlike some other areas of the country, irrigation in Maryland is intended to supplement annual precipitation events, rather than being the primary source of water. The rise in the average application rate, indicated in Figure 3, implies an increasing dependence on irrigation within Maryland in producing higher yields over the past 40 years.

*Comparative Look at Water Demand in Competing Sectors:*

The growth of the irrigation water demand in Maryland differs from that of the United States, in that irrigation water is primarily supplied by ground water sources, whereas irrigation water in other parts of the county is primarily supplied by surface water sources. In the year 2000 nearly 70 percent of all water used for irrigation in Maryland was supplied from ground water sources compared to just over 40 percent nationwide.

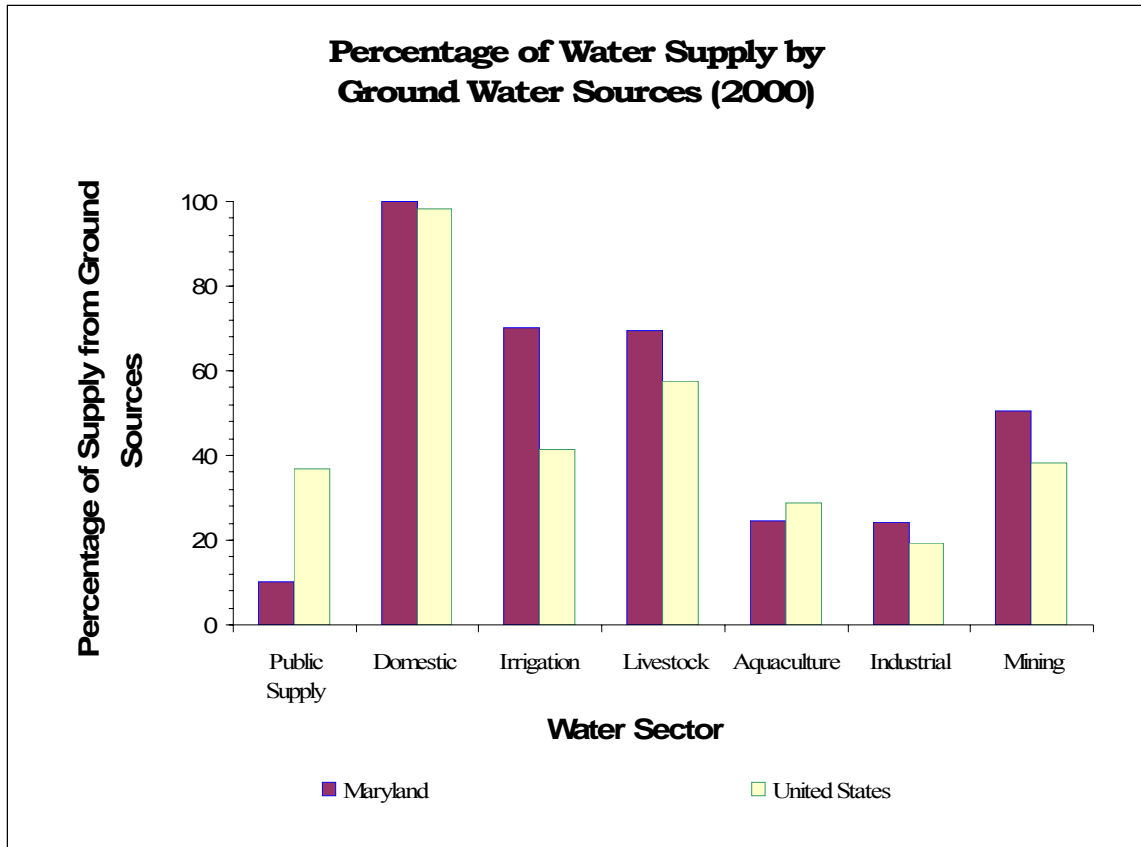
The implication is that as the demand for irrigation water increases in Maryland, diminishing ground water sources will be further taxed; potentially resulting in lower ground water levels and increased salt intrusion along coastal regions. This could potentially have the most significant impact on rural populations that rely entirely upon ground water wells for domestic water use. In the year 2000 over 5 million people in Maryland relied upon ground water sources for their water supply (Hutson et al., 2004).

Figure 4 and Figure 5 present the percentage of water supplied by surface water and groundwater sources, respectively, for Maryland and the United States in general. In addition to domestic supply Figure 5 shows that water consumed for mining activities is substantially supplied by ground water sources. As a result growing irrigation demand could potentially affect mining activities in certain parts of the state, although consumption from mining activities is often removed from agricultural areas and has been on the decline in recent decades, as will be shown in subsequent graphs.



**Figure 4.** Percentage of supply from surface water sources for various water sectors in the United States and Maryland in the year 2000 (Hutson et al., 2004).





**Figure 5.** Percentage of supply from ground water sources for various water sectors in the United States and Maryland in the year 2000 (Hutson et al., 2004).

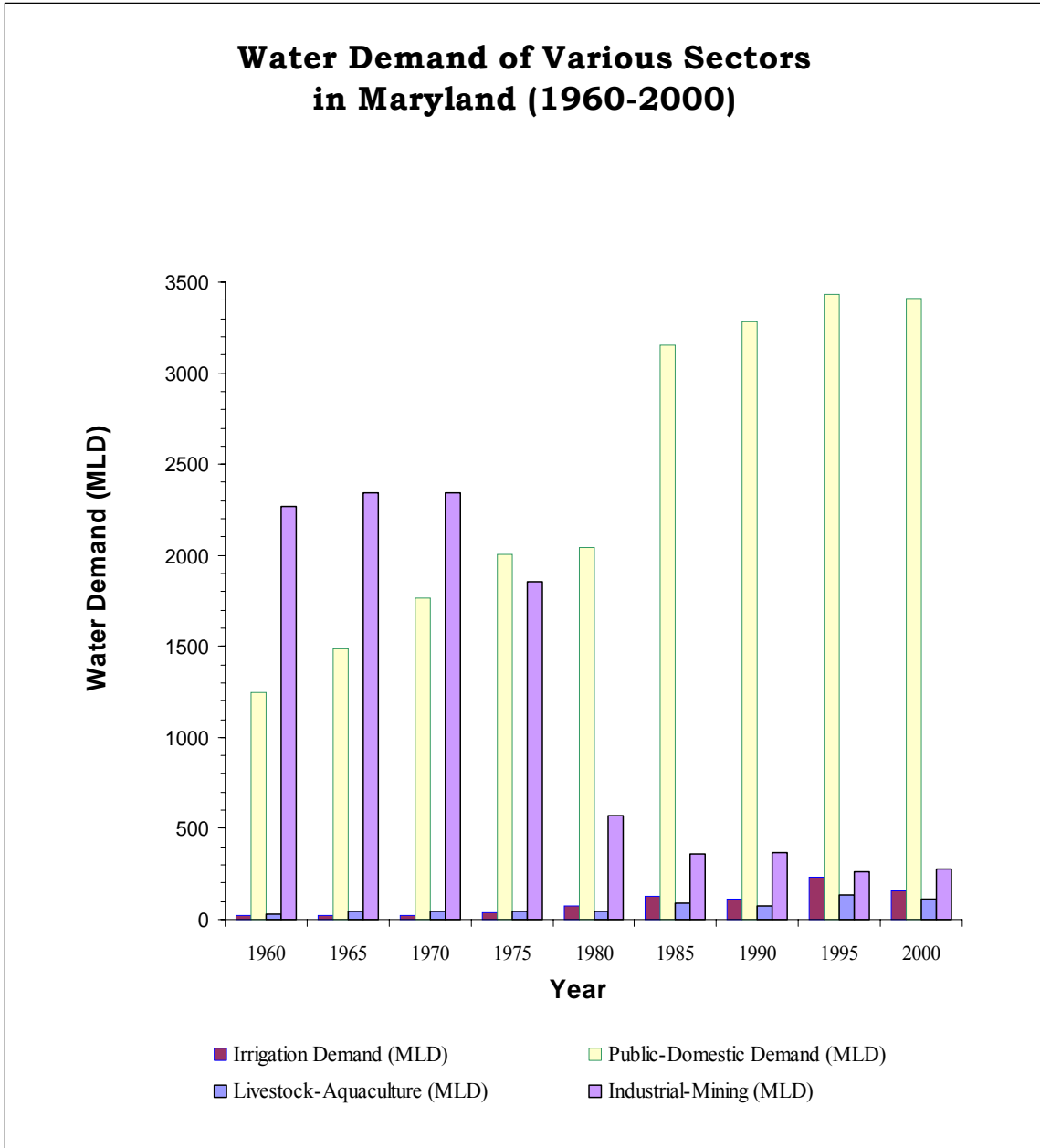
Despite the rapid growth of irrigation demand, compared to other water sectors, irrigation water has played a relatively minor role in Maryland, totaling an equivalent of 5% of the water demand associated with the combined public<sup>1</sup> and domestic<sup>2</sup> sectors. However, in recent years irrigation water demand in Maryland has begun to rival the combined industrial and mining freshwater demand, which has dramatically decreased since the 1970.

On a national level the situation is far different, with irrigation water demand dwarfing other water sectors including public, industrial and other agricultural uses.

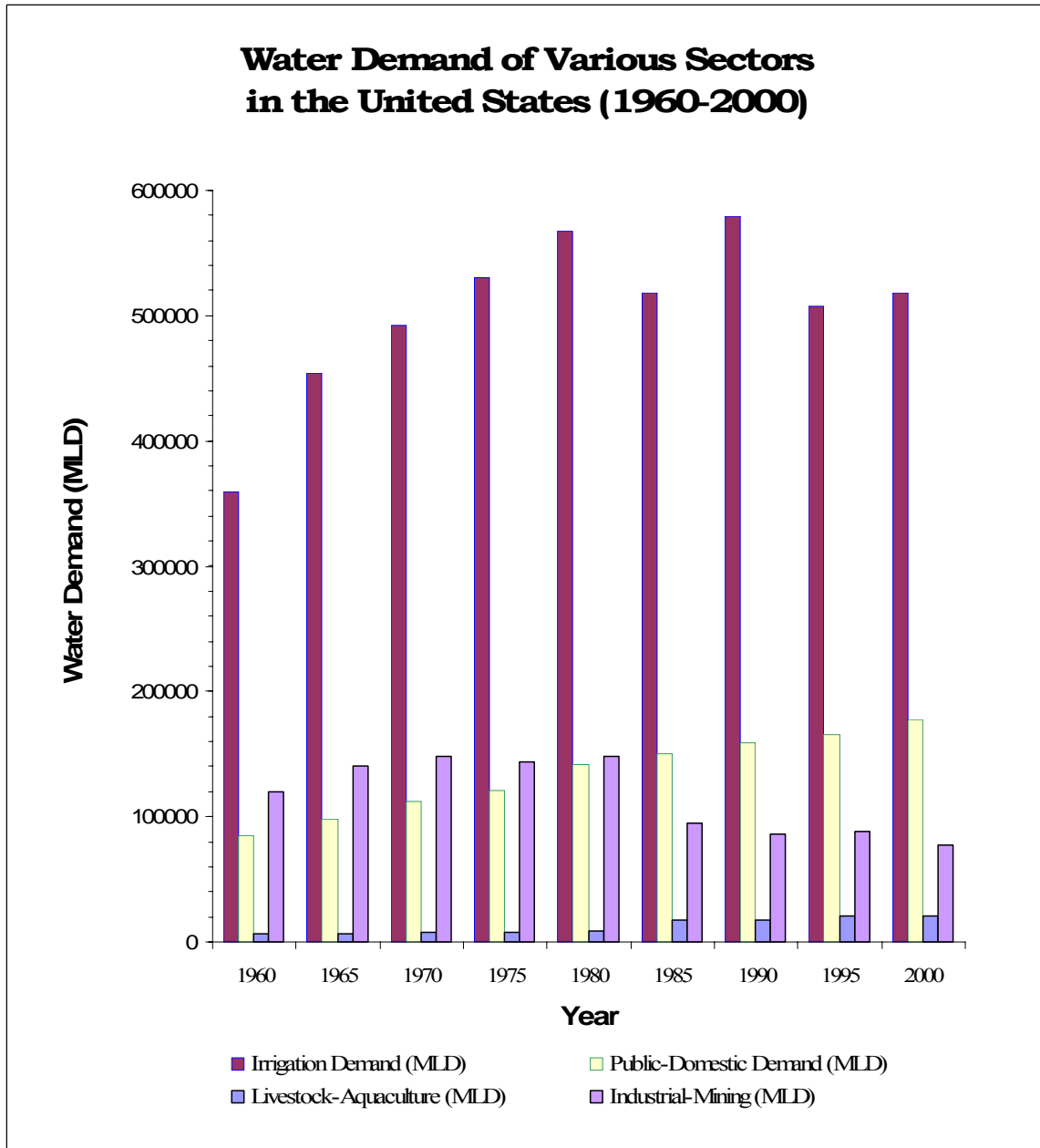
<sup>1</sup> Estimated public supply distributed for residential use.

<sup>2</sup> Estimated water obtained from private wells for domestic purposes.

Figure 6 and Figure 7 present freshwater demand levels for various sectors as reported in USGS circular reports from the year 1960 to 2000. Data show the present water demand values for irrigation, the combined public and domestic water demand, the combined industrial and mining freshwater demand, and other agricultural uses such as livestock and aquaculture. Water demand values for hydroelectric and thermoelectric power have not been included in the comparison below.



**Figure 6.** Comparison of water demand for various water sectors in Maryland from 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).



**Figure 7.** Comparison of water demand for various water sectors in the United States from 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

The comparison shows that while water demand for irrigation in Maryland plays a relatively minor role, irrigation demand is a dominate component of the annual water budget on a national level. When comparing irrigation demand to public/domestic demand, a similar trend is observed, in that public demand has increased over the years in

order to supply a growing population; and yet the rate of increase appears to remain beneath the rate of the population growth due to water conservation measures being implemented in recent decades. This is similar to the trend observed above with regards to the increase in the quantity of agricultural land equipped with irrigation infrastructure, and the decrease in the overall irrigation water demand.

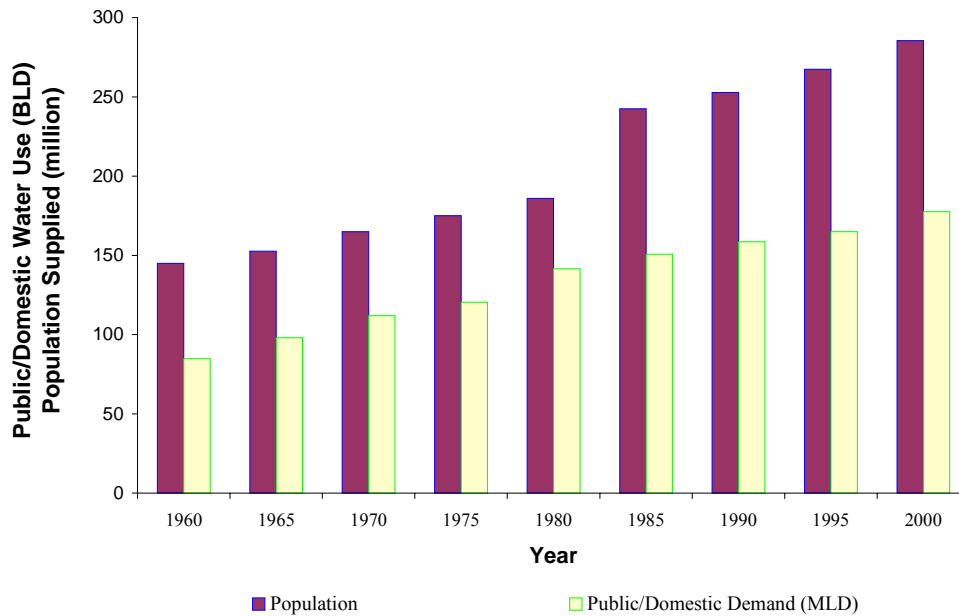
Both on national and local levels, public water use has begun to level as a result of growing environmental consciousness and the development of water conservation technologies implemented over the past two decades, despite a growing population (Wheeler, 2003). Figure 8 and Figure 9 compare the combined public and domestic water demand compared to population growth on a statewide and national level. Both figures show a steady increase in water demand with increasing population. The rate of increase in water demand, relative to population growth, appears to decrease in the years following 1985, particularly in the case of Maryland.

### Public Water Demand Versus Population in Maryland (1960-2000)



**Figure 8.** Public water demand in comparison to population growth in the Maryland from 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

**Public Water Demand Versus Population  
in the United States (1960-2000)**



**Figure 9.** Public water demand in comparison to population growth in the United States from 1960 to 2000 (USGS Circular Reports #398, 556, 676, 765, 1001, 1004, 1081, 1200 and 1268).

The continued population growth is likely to pressure the expansion of irrigation as farm managers attempt to maximize agricultural production in order to meet growing demands given limited land and water resources. As a result, the refinement of irrigation technology and management strategies will need to continue to progress in order to make optimal use of limited water resources.

*Irrigation in Temperate Zones:*

Although irrigation is usually associated with arid regions, there is strong evidence that suggest supplemental irrigation is profitable even in more humid climatic zones (Kramer and Boyer, 1995). Occasional periods of reduced rainfall or drought do cause water stress thereby negatively affecting crop growth and productivity, which in

turn reduces the economic profitability of agriculture during years of poor rainfall. Therefore, supplemental irrigation is the only way to maintain high crop yields and increase profitability during periods of poor precipitation.

During such dry seasons, supplemental irrigation can be used to maintain high crop yields and ensure economic vitality. Moreover, a study on climate variability and its potential effects on available water resources and resource demands, overseen by the Interstate Commission on the Potomac River Basin (ICPRB), predicted the possibility of a ‘substantial increase in the year 2030 [of] summer water use’ as a result of climate change predications made by several atmospheric models.

Carbon-dioxide levels worldwide are increasing, a trend that is expected to continue into the foreseeable future as long as fossil fuels are used as a primary source of energy. The net result is an expected temperature rise of 3°C worldwide over the next hundred years, resulting in warmer growing seasons, with an accompanying expected rise in the overall water demand (Roos, 1993). The greatest increase predicted is a 19% increase in the summer water demands in the year 2030 for the Potomac River basin (Wolman et al., 2004). Therefore, it is likely that the need for supplemental irrigation and the percentage of irrigated agricultural lands will increase in the years to come.

However, the use and installation of irrigation technologies comes with its own costs and places additional demand on limited water resources. Therefore, the use of irrigation technologies for supplemental irrigation during drought conditions must be balanced against the economic profitability associated with the expected increase in crop yield in order to maintain maximum efficiency. In this case efficiency is defined as the maximum economic output to minimum economic input. If the expected increase in



yields (the economic output) does not exceed the actual cost of irrigation technology (the economic input), then irrigation installations would not be viable.

The model developed here attempts to cross this gap by determining irrigation installations that would result in maximum productivity, with the highest water use efficiency appropriate for the water cost level applied. Water use efficiency ( $E_c$ ) is defined as the ratio of crop yield to actual evapotranspiration ( $ET_a$ ) given in equation 1 below (Kirda, 2002), where actual evapotranspiration is a reflection of the amount of water used by the crop (either from natural precipitation or applied supplemental irrigation).

$$E_c = \frac{Y}{ET_a} \quad (1)$$

Where,  $E_c$  is the water use efficiency [kg/ha·mm],  $Y$  is the crop yield [kg/ha], and  $ET_a$  is the actual evapotranspiration [mm].

Alternatively, water use efficiency may be gauged by the irrigation water efficiency, which is defined as the ratio of water used by the crop (the effective water use) to the total amount of water applied (Karagiannis et al., 2002). Irrigation water efficiency depends upon the type of irrigation technology employed, the environmental conditions, land characteristics, and irrigation scheduling.

The model developed within this research considers meteorological data from the past 30 years to determine if irrigation installation costs are justified. Model simulations are used as a basis for the projection of this justification for future farm investments. For the most part, Maryland farmers without supplemental irrigation take a gamble each year

that the precipitation throughout the growing season will be sufficient to meet their needs. During years of reduced precipitation, where yields are below normal, they absorb an economic loss or receive subsidies from insurance agencies or governmental protection programs. Investment in irrigation technology offers a safeguard during years of reduced precipitation. The installation cost of a supplemental irrigation system is justified if the projected economic return over the expected life of the irrigation system exceeds the installation and operation costs associated with the chosen irrigation system.

Determining the potential economic return due to increases in crop yield as a result of irrigation installation is a means of justifying irrigation installation costs; although the stochastic characteristic of precipitation and weather conditions does not guarantee that past performance will exactly reflect future conditions. This is especially true considering the abnormal drought conditions associated with 1999-2002. This problem is addressed, to some degree, by the use of a weather generator component of the SWAT model, as is discussed in more detail later in this text.

Irrigation programs must include the use of efficient technologies and well managed practices if water conservation is to be achieved particularly during periods of low precipitation. Current national trends show an increase in water use efficiency as technology develops and management practices are refined. If this trend continues it will be possible to irrigate more land with a less significant increase in water consumption as indicated by historical trends. An example of this is seen in Israel where the total irrigated land area was increased by 30% from 1958 to 1969 without a parallel increase in the total water supply to agriculture, due primarily to more efficient means of application (Kramer and Boyer, 1995).

The case of Israel differs from that of Maryland in that irrigation and water conservation practices are a greater necessity in Israel, and encouraged through both economic and political incentives and pressures that are not applicable to Maryland and the United States in general. However, it can be assumed that as competitive demand for limited water resources increase, in Maryland and elsewhere, water conservation technologies will be favored for both agricultural and domestic use.

To maximize profitability, supplemental irrigation must be applied only when the increase in revenue due to higher yields exceeds irrigation costs. A relatively new area of interest in the agricultural industry is that of 'deficit irrigation,' which is an agricultural practice where water supply is maintained below maximum levels allowing for mild water stress on crop species with minimal effect on crop yields (Kirada, 2002). A modest and acceptable irrigation deficit level depends on the crop species and the growth stage in the life cycle of the crop in which such a deficit is suffered. This practice may result in substantial water cost savings, particularly in areas of water scarcity or high water cost, with only minimal negative effects on crop yield.

The determination of an appropriate irrigation deficit necessitates extensive knowledge of crop response to available water supply, and knowledge and predictability of water balance parameters in the soil-plant-atmosphere system. This knowledge is essential in order to achieve maximum water use efficiency values by limiting or eliminating irrigations that have little or no beneficial impact on yield. Moreover, withholding water may be beneficial by controlling diseases, improving crop quality and regulating the maturation timing of the crop as a whole (Hargreaves and Samani, 1984).

### **Irrigation Water Demand and Scheduling:**

Isrealsen and Hansen (1962) define three major considerations that influence irrigation scheduling: the water needs of the crop, the capacity of the root zone to store water, and the availability of water for irrigation. The water needs of the plant are primarily reflected in the evapotranspiration potential, which is determined by the physiological characteristics of the plant species, and the prevalent meteorological and environmental conditions associated with the plant's habitat or location. However, plant water needs are relative to the objectives of the farmer or horticulturalist to achieve a certain goal. If optimal growth is to be achieved, which in the case of agriculture is objectively reflected by maximum crop yield, then water demand, at its peak, is equal to the maximum evapotranspiration rates.

In the general case, agricultural objectives are to achieve maximum profit for the farmer, which may result in a target yield that is slightly below maximum crop yields, if the cost of required inputs, water in this case, exceeds the marginal return expected from maximum crop yields. In such a case it may be desirable to adjust plant water supply to below maximum levels.

Therefore, irrigation requirements must be adjusted to achieve the objectives of the producer, which is maximum benefit. The degree to which irrigation water demand, the demand required to achieve maximum benefit, is equal to, or approaches, the total water demand of the plant species, depends on a number of factors including: water availability and cost, crop value, precipitation and irrigation installation and maintenance costs. Hargreaves and Samani (1984) found four cases in which irrigating for maximum yield is more likely to produce maximum benefit. These cases include: 1) land is limited

or highly valued, and water is abundant; 2) crop value is high; 3) rainfall makes little contribution to crop supply; and finally 4) when irrigation costs are low.

The degree to which the circumstances of the farm manager deviate from the circumstances above, the greater is the irrigation deficit that can be tolerated before irrigation is of benefit. In cases where water scarcity is more severe this paradigm may shift from maximizing profit to maximizing water use efficiency (Stewart and Hagan, 1973), in which a new set of standards must be applied to assess crop irrigation needs.

The second primary consideration in irrigation scheduling identified by Isrealsen and Hansen (1962) is the capacity of the root zone to store water, which is determined by the texture and structure of the soil matrix. High clay content, as well as large amounts of organic matter, increase the storage holding capacity of soils (Kramer and Boyer, 1995). Both clay content and organic matter levels can vary significantly within a region or watershed or even within the same field. Moreover, the volume of water available to the plant varies with root depth, which gradually increases during the growing season to a maximum depth. For this reason some croplands may be in greater need for more frequent irrigation than others within the same climatic zone depending on soil conditions and the growth stage of the plant. It is, therefore, critical to identify those regions that will profit most from the installation of an irrigation system, if effective water resource use is to be achieved.

The third consideration in irrigation scheduling, identified by Isrealsen and Hansen (1962), is that of the availability of water for irrigation, which is by far the most perplexing and subjective consideration to make. The availability of water involves the determination of the needs of competing sectors of society, and the allocation of specific

portions of this resource to serve a certain purpose. Implicit in this consideration is the value of water, and the real or perceived value of each sector or industry that consumes this limited resource.

From a resource management perspective the value and allocation of water resources have deep rooted social, economic, political and environmental considerations. In humid locations where abundance of supply is in excess of the total demand for all sectors of society, the availability of water is not a significant concern. However, in an increasing number of countries, scarcity of supply places constraints on the use and availability of water, requiring that difficult management decisions be made concerning prioritizing the use and distribution of water.

A watershed level irrigation model, developed in this study, aids in the evaluation of these considerations by allowing regional planners or large landowners to determine the relative impact of irrigation on various portions of the area of interest and to make decisions based on these judgments. Buchleiter et al. (1996) identify three potential objectives of irrigation scheduling: 1) to reduce production cost, 2) increase yields, and 3) improve integration of water management with the overall crop production system.

These objectives are generally achieved at the field scale level, for which there are several irrigation scheduling programs calibrated to specific climatic zones and agricultural practices that aid the farmer in maximizing water use efficiency for a given field-crop-climate combination. However, the added benefit of the project revolves around the development of a regional scale irrigation model that will allow planners to maximize productivity of water resources and better justify the allocation of water resources where competing sectors of society are involved.

This is accomplished through the use of a GIS information management base, in which a tremendous amount of spatial data, needed for model calculations and simulations, can be stored on land use, topography, agricultural practices, crop types, and soil properties for a widely varied heterogeneous terrain. These attributes are then associated with each carefully defined spatial unit, and are then readily available for use as actual values for required model parameters. Once the model is implemented, values such as soil-water content, runoff depth, sediment accumulation, vegetative growth and the like, associated with each spatial unit can be determined, updated and modified as the model simulation progresses. This versatility allows the user to look over a wider landscape when determining irrigation demand for a given region, as opposed to narrowly considering the needs of a single field-crop combination.

The hydrological model selected for this project, in order to monitor water movement through the landscape, is the SWAT (Soil and Water Assessment Tool) model. The SWAT model has been selected for several reasons, but primarily because it is a physically based, computationally efficient model that uses readily available inputs. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large watersheds; and at its core is a robust, fundamentally sound hydrologic model (Neitsch et al., 2002a). Despite the particular transport problem under study, the driving force is water movement and the overall water balance, which makes SWAT a reasonable model to be used as a basis for determining plant water needs.

The use of SWAT also allows us to perform irrigation analysis in both a stochastic and deterministic manner, which is particularly useful in the estimation and

projection of future agricultural water requirements under a variety of conditions. SWAT requires the incorporation of meteorological data over successive years from which it can determine mean and variance values for temperature, precipitation, humidity, wind speed and other relevant meteorological data. From this information the weather generator component of SWAT can generate representative weather values for a given time of the year, based on the mean and variance parameters obtained. This allows the user to project simulations that incorporate realistic, but randomly generated, weather parameters, thus helping to justify irrigation investments on a generated representative weather pattern as opposed to actual values.

Alternatively, SWAT allows the user to supply actual historic meteorological values and run the model based on these values alone. This type of analysis is necessary in determining realistic current irrigation schedules and water demand, or when comparing actual water demand with optimal demand based on crop production and economic benefit. Thus, the versatility of SWAT in running simulations with both simulated and actual weather data allows the user to achieve varied objectives, and increases the utility of the model as a resource management tool. Moreover, SWAT is a well-developed model that has undergone extensive validation and has been widely used under various conditions (Neitsch et al., 2002a), and can, therefore, be relied upon to produce accurate and realistic results.

The development of the supplemental irrigation economic application is done in Microsoft Visual Basic that incorporates SWAT input and output files, thereby utilizing ArcView GIS values and SWAT variables and calculations. The interaction of these three components: the storage and organization of spatial information into a GIS



framework, the execution of a physically based hydrologic model (SWAT), and the incorporation and execute of a custom Visual Basic application that will include specially defined algorithms used for irrigation economic analysis, is therefore essential to the completion of this project.

Since its creation SWAT has been calibrated and validated by numerous researches both here in the United States and internationally, mostly to model water quality variables in the environment, and is therefore considered to be a trusted and reliable model. Examples, showing the diversity of climates and regions where the model has been used and calibrated as well as the wide range of purposes, include a study conducted on the Maryland Piedmont region, which utilized 6 years of hydrological data to calibrate and validate the capabilities of SWAT (Chu and Shirmohammadi, 2004). Another example includes a study conducted in the Vantaanjoki basin in Finland where the model was used to determine nitrogen and phosphorus concentrations in the stream outlet, and calibrated using data collected over a period of 9 years (Grizzetti et al., 2003). In the rural hilly midlands in the state of Hesse, Germany, the model has been used to predict the environmental impacts of deforestation and increased crop production prior to development (Fohrer et al., 2001 and Fohrer and Frede, 2002). The model has also been used for the Nagwan watershed in India to identify and prioritize critical sub-watersheds in need of soil conservation management practices (Tripathi et al., 2003). This particular region of the world is characterized by heavy rainfall during the monsoon season, and was therefore in need of conservation practices although the strategic prioritization was often difficult. The validation and calibration was done using data collected over a 6 year period.

The few examples above are intended to show the breadth of climates and regions where the model has been validated and used, in order to give credence to the use of the SWAT model in Maryland. Because of the range of use and extensive development of the SWAT model, it is accepted as a robust system for application in these very divergent climatic conditions.

Overall SWAT has been shown to have reasonable predictive capability when used for long-term analysis. The broad comprehension, versatility and robustness of the model makes it a valuable tool in the assessment and prediction of water quality values under a wide range of circumstances, and will undoubtedly continue to be an invaluable tool to regulators, developers and conservationists.

Moreover, SWAT has the flexibility to allow for auto-irrigation and auto-fertilizer management options (Neitsch et al., 2002a). In this case applied irrigation can be withdrawn from sources inside or outside of the watershed. This feature will allow the user to model the impact of irrigation demand on local water supplies. Furthermore, because of SWAT's ability to monitor non-point source pollutants, the model is used to determine the environmental impact of irrigation on sediment and nutrient transport processes, which is an important secondary objective of this study.

### **The Water Balance:**

Critical to determining optimal supplemental irrigation requirements and crop demand is the evaluation of available water in the soil profile, which can be determined by accurately modeling the water balance within the soil-plant-atmosphere system. As is discussed in the pages that follow, irrigation events must be scheduled once the soil-water level within the root zone drops to a predetermined set point that varies for the soil-crop

combination. The general water balance within the root zone of the soil profile is determined by the soil-water balance equation shown as equation 2 below.

$$\Delta R = (P_e + V_z + I_d + G_c - ET_a - DP) \cdot \Delta t \quad (2)$$

Where,  $\Delta R$  is the soil-water variation during time interval  $\Delta t$  [mm·hr],  $P_e$  is the effective precipitation [mm],  $V_z$  is the water stored in lower layer of thickness  $z$ , explored by roots after equivalent root growth during time interval  $\Delta t$  [mm],  $I_r$  is the irrigation water depth applied [mm],  $G_c$  is the groundwater contribution [mm],  $ET_a$  is the actual evapotranspiration [mm],  $DP$  is the deep percolation [mm], and  $\Delta t$  is the time interval [hr].

The water balance oscillations can be divided into two phases (Thornthwaite and Mather, 1955). The first corresponds to a drying period when the potential evapotranspiration ( $ET_p$ ) exceeds the effective rainfall ( $ERF$ ), in the form of precipitation or irrigation, during which time a moisture deficit occurs. The second phase corresponds to a recharge phase, when the effective rainfall exceeds the potential evapotranspiration, during which time the soil-water rises to maximum levels, replenishing the soil profile, while excess water is lost as a result of runoff or deep percolation.

During the drying phase (when  $ET_p > ERF_t$ ) the soil-water content is estimated from equation 3 below, and the actual evapotranspiration rate is determined by equation 4, using the water balance approach (Mannocchi and Mecarelli, 1994).

$$\frac{\theta_t}{U} = \exp\left[\frac{(ERF_t - ET_{pt})}{U} + \ln \frac{\theta_{t-1}}{U}\right] \quad (3)$$

$$ET_a = (\theta_{t-1} - \theta_t) + ERF_t \quad (4)$$

Where,  $\theta_t$  is the soil-water content at time =  $t$  [mm],  $\theta_{t-1}$  is the soil-water content at time =  $t-1$  [mm],  $ERF_t$  is the effective rainfall at time =  $t$  [mm],  $ET_{pt}$  is the potential evapotranspiration at time =  $t$  [mm],  $ET_a$  is the actual evapotranspiration [mm], and  $U$  is the usable soil-water capacity [mm].

During the recharge phase, when  $ET_p < ERF_t$ , the soil-water content can be estimated using equation 5 (Mannocchi and Mecarelli, 1994). During this phase the actual evapotranspiration is at a maximum, and is equivalent to the potential evapotranspiration rate ( $ET_a = ET_p$ ).

$$\theta_t = \theta_{t-1} + (ERF_t - ET_{pt}) \quad \text{when } 0 \leq \theta_t \leq U \quad (5)$$

Where,  $\theta_t$  is the soil-water content at time  $t$  [mm],  $ERF_t$  is the effective rainfall at time  $t$  [mm],  $ET_p$  is the potential evapotranspiration [mm], and  $U$  is the usable soil-water capacity [mm].

The equation above is valid for periods of recharge only. Once the soil-water content has reached the maximum soil-water capacity ( $U$ ), the soil recharge is complete and the soil-water content reaches saturation ( $\theta_t = \theta_s$ ), and any excess water results in runoff or deep percolation.

The greatest loss of water from the soil profile occurs as a result of evapotranspiration, which is the primary component of the soil-water balance equation (Allen et al., 1989). Therefore, the accurate determination of evapotranspiration values is of primary importance in the determination of available water within the soil profile from which irrigation requirements are derived. For the purposes of this model evapotranspiration values are determined using the Penman-Montieth equation incorporated into the SWAT model. Because of the paramount importance of evapotranspiration values a considerable amount of time is spent, in Appendix A of this document, on the development and explanation of evapotranspiration equations used in the model. Although it should be noted that evapotranspiration is only one component of the soil-water balance equation.

Evapotranspiration and remaining hydrological components of the water balance equation, including deep percolation, the upward flux, water storage, and surface and subsurface flow, are best determined using a watershed scale hydrological based model such as SWAT. These components are often dependent on inward and outward water flows of adjacent units of land, and are therefore, best modeled as a whole, when looking at specific points within a wider landscape. SWAT will, therefore, be used as a basis for analyzing water movement and soil-water availability within an area of interest. Upon this framework the independently developed irrigation economic model is applied, in order to determine if irrigation is recommended and the potential agricultural water demand for each location. An expert system can then be used to determine areas of greatest potential for irrigation development.

**The SWAT Model:**

SWAT is a river basin/watershed scale model developed to evaluate and quantify the impact of land management practices on runoff, subsurface flow, groundwater, erosion and sediments, nutrients, and pesticide losses in large watersheds (Arnold et al., 1993). SWAT is written in FORTRAN and was developed as an extension of a previous watershed model, the Simulator for Water Resources in Rural Basins model (SWRRB), and incorporates algorithms from the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems; Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator; Williams) models for processes occurring on land, and uses some algorithms from the QUAL2E (Enhanced Stream Water Quality; Brown and Barnwell, 1987) model for in-stream water quality processes.

SWRRB, the basis for SWAT, was limited in use to watersheds up to a few hundred square kilometers in size, with a maximum of 10 subbasins. The need to simulate stream flow for larger basins, extending over several thousand square kilometers lead to the development of ROTO (Routing Outputs to Outlet), which could link multiple sessions of SWRRB together in order to overcome these limitations (Neitsch et al. 2002a). In response, SWAT was developed to overcome this cumbersome process and monitor water movement through extensive areas.

SWAT was developed in the early 1990's, and has since undergone continual revisions and improvements (Neitsch, 2002b). Various components of SWAT model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management associated with a given watershed (Srinivasan et

al., 1998). The hydrological processes simulated include surface runoff, calculated from daily simulated or measured rainfall values; percolation, modeled by a layered storage technique, where water fills layers sequentially; lateral subsurface flow; groundwater flow to streams and shallow aquifers; evapotranspiration; snowmelt; transmission losses from streams; and water storage and losses from ponds.

SWAT is a physically based model and requires specific information on climate conditions, soil properties, topography, vegetation and land management practices. Climatic inputs required by SWAT that drive these hydrological processes include: daily precipitation, maximum and minimum air temperature values, solar radiation, wind speed and relative humidity. Weather and hydrological factors are used to compute sedimentation yield, crop growth and nutrient and agricultural chemical transport. Agricultural management practices including irrigation, tillage, fertilization, and residue decomposition, can be included in the model as options in order to simulate their effect on sedimentation, crop growth, and chemical transport.

Using these inputs, the physical associations of water movement, sediment transport, crop growth, and nutrient cycling are directly modeled by SWAT (Neitsch et al., 2002a). The basic information required to make the model run is generally available from various government agencies. The model allows the user to model the impact of management practices, climatic or environmental changes and water quality very effectively without a great deal of investment. The model is a continuous model designed to study long-term impacts using a daily time step. The model is not designed to simulate detailed single-event flood routing, and generally does not provide accurate results for short-term events (Neitsch et al., 2002b).

For modeling purposes the watershed is divided into subbasins spatially dominated by different land use and soil properties, each of which can be referenced by the user. Each subbasin is organized according to input information on climate, ponds/wetlands, reach or main drainage channels, and hydrologic response units (HRUs), which are user defined portions of the subbasin that possess unique land use, management or soil properties (Neitsch et al., 2002b). HRUs are not synonymous with fields, but rather represent all areas within a subbasin with a specific soil type, land use, and management combination. Unlike subbasins, HRUs do not have to be contiguous units, but rather includes all parcels of land within the subbasin with similar properties.

The component processes of SWAT are modeled for each HRU and then linked continuously over the entire watershed. A discussion of each of these components is provided in Appendix A of this document and is gleaned from the SWAT technical documentation (Neitsch et al., 2002a).

### **Crop Yield Response:**

Of fundamental importance to this study is an understanding of crop growth and the factors that affect the crop yield response. The following overview discusses the pertinent factors involved, and provides an explanation of how crop yield response to irrigation is incorporated into the model developed in this study.

In determining the economic profitability of irrigation it is essential to know the crop yield response to water stress for all crop varieties of interest. Water stress is observed when actual evapotranspiration rates deviate from potential evapotranspiration rates, as a result of which crop response can be impaired. When  $ET_a = ET_p$ , available water is sufficient to meet the entire plant water demand and, as a result, plants grow at



their optimal rate, thus maximizing yields for the given environmental conditions.

Maximum yield, as used in this report, is defined as the harvested or expected yield of a 'high producing variety well-adapted for the local growing environment where water, nutrients, pest and disease do not limit yield' (Doorenbos and Kassam, 1979).

As this definition implies, there are several factors that influence yield, including: fertilizer application, salinity levels, pests and diseases, irrigation application methods and agronomic practices. Consequently, several empirical functions have been determined relating such factors as planting density and nitrogen/fertilizer concentration to yield in order to determine optimal levels for various crop species (Hargreaves and Samani, 1984). Production levels have also been found to be a function of available energy. Stewart and Hash (1982) found a linear relationship between maximum yields and mean seasonal Class A pan evaporation (a reflection of radiation energy received) for maize cultivars. As a result, maximum yield is a relative term that may vary from season to season and with changing environmental conditions.

Therefore, for the purposes of this paper, maximum yield is assigned a value of 1.0, with actual yields being a percentage of maximum yield, assuming all growing conditions are the same with the exception of water availability. The determination of empirical crop yield response factors ( $k_y$ ), used to estimate expected crop yield with respect to water deficit is done under optimal or standard conditions with respect to agronomic practices, fertilizer application and soil conditions with high producing varieties well-adapted to the environmental conditions (Doorenbos and Kassam, 1979). Experimental testing of crop yield response factors occurred with all inputs held at

optimal levels with the exception of water, which is held within a 50 to 70% deficit during the growth stage under review.

In cases where crop production is carried out under a known or intentional irrigation deficit, fertilizer application may be reduced to account for the decrease in crop yield from optimal conditions, in order to achieve additional savings. Crop nitrogen requirements can be approximated by crop yield functions that show nitrogen requirements can be expressed as a function of actual evapotranspiration rates. In the case where actual evapotranspiration rates deviates from potential evapotranspiration nitrogen application can be determine by the empirical relationship shown by equation 6 (Hargreaves, and Samani, 1984). Values for the empirical coefficient ( $KN$ ) are obtained from Shalhevet et al. (1979), examples of which are listed below for some of the most common food crops.

Typical  $KN$  values for common food crops:

<u>Crop</u>	<u><math>KN</math> Value</u>
Corn	0.32
Wheat	0.12
Cotton	0.10
Sugar Beets	0.15

$$N_a = KN \times ET_a \quad (6)$$

Where,  $N_a$  is the required nitrogen application [kg/ha],  $KN$  is the empirically determined constant for crop variety [dimensionless], and  $ET_a$  is the actual evapotranspiration [mm].

Note that the equation above can be used to estimate excessive fertilizer application on agricultural fields where supplemental irrigation systems are not present during periods of reduced precipitation. If we assume that, at the beginning of each growing season or at set points during the growth cycle, fertilizer application is applied in sufficient quantity for maximum growth, then during periods of reduced precipitation the quantity of excess nitrogen can be estimated as the difference between nitrogen requirements for potential evapotranspiration and actual evapotranspiration. This value may give an indication of the maximum potential reduction in non-point source pollution achievable in cases where supplemental irrigation can compensate for the water deficit caused by reduced precipitation.

Research has shown that crop yield response varies with the growth stage in which an irrigation deficit is suffered (Kirda and Kanber, 1999). An irrigation deficit suffered at one stage in the growth cycle of the crop may have little to no significant effect on crop yield, while an irrigation deficit suffered at a more critical stage in the plant cycle (generally during the flowering, fruit setting or grain formation stage) may dramatically affect yield (Kirda, 2002). For example, soybean yields decrease significantly more when an irrigation deficiency occurs during the flowering and pod development stages, when compared to an irrigation deficiency suffered during the vegetative growth stage (Kirda, 2002). Therefore, consideration must be given to the stage of the plant in its growth cycle if the value of supplemental irrigation is to be determined.

As a result a series of empirically derived crop yield response factors ( $k_y$ ) have been developed corresponding to irrigation deficits suffered at specific stages in the

growth cycle, and for a continuous irrigation deficit suffered over the entire growth cycle. Crop response factors ( $k_y$ ) relate the relative yield decrease to the relative evapotranspiration deficit caused by a lack of adequate water.

Crop yield response factors for a variety of crop species have been independently measured by the Food and Agriculture Organization of the United Nations (FAO) and the International Atomic Energy Agency (IAEA). The results have been published in a technical document of the IAEA (IAEA, 1996) and in a book by Kirda et al. (1999), which compiles the IAEA and FAO research findings, respectively. In both cases a series of measurements were conducted under reduced supplemental irrigation conditions, where soil-water deficit thresholds varied from 50-70 percent. Crop yield response factors were measured for reduced irrigation water sustained throughout the growing season, and for reduced water conditions suffered at four specific growing stages as follows (Moutonnet, 2002): i) initial –planting to 10% ground cover; ii.) crop development –10% percent ground cover to effective full cover and initiation of flowering; iii.) mid-season –effective soil cover to full maturity; iv.) late season –onset of maturity to harvest.

Table 1 below lists the crop response factors determined by the FAO for a number of common crop species. The values included measure the crop yield response factor for a continuous irrigation deficit suffered throughout the growth season, indicated by the treatment code  $Tr_{.0000}$ , and for short term irrigation deficits suffered at each of the four physiological growth stages, which are labeled according to the treatment codes  $Tr_{.0111}$ ,  $Tr_{.1011}$ ,  $Tr_{.1101}$ ,  $Tr_{.1110}$ , respectively (Kirda et al., 1999).

**Table 1.** FAO crop yield response factors ( $k_y$ ) (Kirda et al., 1999).

Crop:	Crop Yield Response Factors ( $k_y$ )				
	Tr <sub>.0000</sub>	Tr <sub>.0111</sub>	Tr <sub>.1011</sub>	Tr <sub>.1101</sub>	Tr <sub>.1110</sub>
Bean	1.15	0.20	1.10	0.75	0.20
Cotton	0.85	0.20	0.50	N/A	0.25
Groundnut	0.70	0.20	0.80	0.60	0.20
Maize	1.25	N/A	N/A	N/A	N/A
Potato	1.10	0.60	N/A	0.70	0.20
Sorghum	0.90	0.20	0.55	0.45	0.20
Soybean	0.85	0.20	0.80	1.00	N/A
Sugar Cane	1.20	0.75	0.50	0.50	0.10
Sugar Beet	0.85	N/A	N/A	N/A	N/A
Sunflower	0.95	0.40	1.00	0.80	N/A
Winter Wheat	1.00	0.20	0.60	0.50	N/A

A crop yield response factor, greater than one, indicates that the yield decrease is proportionally greater than the associated relative difference between the potential and actual evapotranspiration. Therefore, crops with a crop yield response factor ( $k_y$ ) of less than one can generate more significant savings in irrigation cost under controlled irrigation deficit conditions. The overall seasonal values listed in Table 1, for an irrigation deficit suffered throughout the growing season, are used in the irrigation economic application to predict potential or maximum yield based on the irrigation deficit suffered and actual yield values, as obtained from the SWAT model.

Some studies have shown that an irrigation deficit suffered at specific stages may increase crop quality, while only moderately affecting yield (Kirda, 2002). Examples include a marked increase in the protein content and baking quality of wheat, the length and strength of cotton fibers, improved quality and flavor of fruits, and an increase in the sucrose content of sugar beet and grapes, under controlled deficit irrigation. Studies have also shown that periods of reduced growth at specific stages, caused by deficit irrigation, may in fact trigger physiological processes that can increase harvested yields, these

include flower-induction, early ripening of grains, and increased root development (Smith and Kivumbi, 2002). By triggering a sudden ripening of the entire yield, the field can be harvested in one operation, resulting in greater efficiency and use of resources, leading to potential savings in labor and equipment costs, when compared to staged ripening of the harvest over a given time frame, requiring multiple harvest operations or more significant fruit loss.

Vaux and Pruitt (1983) fitted a linear equation to crop yield response data for deficit irrigation conditions, which relates the relative crop yield deficit (based on decreases from the expected maximum yield under optimal irrigation conditions) to the relative evapotranspiration decrease caused by irrigation deficit conditions.

$$1 - \frac{Y}{Y_m} = k_y \left[ 1 - \frac{ET_a}{ET_p} \right] \quad (7)$$

Where,  $Y$  is the expected crop yield [kg/ha],  $Y_m$  is the maximum crop yield [kg/ha],  $k_y$  is the a crop yield response factor [dimensionless],  $ET_a$  is the actual evapotranspiration [mm],  $ET_p$  is the potential evapotranspiration [mm].

The crop yield response factor ( $k_y$ ), used above, varies with crop species, variety, and the growth stage during which the deficit evapotranspiration is experienced. The crop yield response factor gives an indication of the crop tolerance to drought conditions. As stated above, the relative decrease in crop yield is dependent on the stage of growth the deficit is suffered. An irrigation deficit suffered at multiple points during crops development, may result in a cumulative effect on yield deficit. This is an important

consideration as precipitation in more temperate climates may be sporadic and unpredictable. Therefore, a significant negative effect on crop response can occur if an irrigation deficit, of a short duration, occurs at a critical stage during plant development, even if the overall precipitation for the growing season is adequate or even above average. Therefore, annual precipitation is not an accurate indication or guarantee that an irrigation deficit has not occurred.

An alternative equation for water use efficiency may be developed by solving for crop yield ( $Y$ ) in equation 7 and substituting it into equation 1 to obtain;

$$E_c = \frac{Y}{ET_a} = \left[ k_y - \frac{k_y - 1}{ET_a / ET_m} \right] \times \frac{Y_m}{ET_m} \quad (8)$$

The factors discussed above, primarily the components of the hydrologic model, the meteorological model, and factors involved in the growth cycle of the crop as related to yield, are the principle modeling components involved in the determination of irrigation water demand.

### **Existing Irrigation Models:**

Irrigation scheduling models aim at timing irrigation events in order to replenish soil-water once a certain minimum soil-water threshold has been reached. There are currently several irrigation scheduling models that exist, but vary slightly with regards to their methods and procedures. The following discussion is intended to introduce the methodology of a few irrigation scheduling programs in order to conceptualize how

irrigation schedules are determined and to evaluate which procedures can best be adapted for use with SWAT for determining irrigation needs on a regional or watershed scale level. Three irrigation scheduling programs are presented below and represent three significantly different approaches based upon the slightly varied objectives for which they were developed.

*ISAREG Model:*

In general, two types of irrigation simulation models exist: water flux simulation models, which compute water fluxes entering and exiting the root zone; and water balance simulation models that estimate the input and output quantities of water to the soil reservoir within a certain time step. The ISAREG model is of the latter category utilizing a water balance simulation model in order to establish irrigation programs for a single soil-climate-crop combination (Pereira et al., 2003). ISAREG is a field scale model designed to establish irrigation programs with daily, deca-daily or monthly time steps (Pereira et al., 2003). The current version of ISAREG is combined with the EVAP56 model used to compute reference evapotranspiration ( $ET_0$ ), and the KCISA model used in computing the required crop parameters.

Similar to the soil-water balance equation used by SWAT, the following equation is used to calculate the soil-water content for the complete effective rooting depth. This equation differs somewhat from the soil-water balance equation presented previously, in that this current equation computes volumetric soil moisture values (the quantity of water per unit soil volume) as opposed to strictly the quantity of water, and is presented as;

$$\theta_i = \theta_{i-1} + (P_i - Q_{ri} + I_{ni} - ET_{ai} - DP_i + GW_i)/(1000z_{ri}) \quad (9)$$



Where,  $\theta_i$  is the average soil-water content in the root zone [mm/mm] on day  $i$ ,  $\theta_{i-1}$  is the soil-water content on the previous day [mm/mm],  $P_i$  is the precipitation on day  $i$  [mm],  $Q_{ri}$  is the runoff from the soil surface on day  $i$  [mm],  $I_{ni}$  is the net irrigation depth on day  $i$  [mm] (infiltrating the soil),  $ET_{ai}$  is the actual crop evapotranspiration on day  $i$  [mm],  $DP_i$  is the deep percolation on day  $i$  [mm],  $GW_i$  is the upward flux of water from a shallow water table on day  $i$  [mm], and  $z_{ri}$  is the root depth on day  $i$  [m].

This water balance approach computes the quantity of water entering and exiting the soil profile reservoir per unit volume extending from the soil surface to the root depth of the crop ( $z_r$ ), which varies for each plant species and the plants' growth stage. The volume of water being removed from the system as a result of evapotranspiration or deep percolation is dependent on the depth of the available water ( $R$ ). For computational purposes the total depth from the soil surface to the maximum rooting depth can be divided into three volumes or storage zones (Pereira et al., 2003):

- i. The first is the *excess water zone*, which includes the storage volume in excess of the field capacity ( $\theta_{FC}$ ) up to the soil-water at full saturation ( $\theta_s$ ).
- ii. The next storage volume is referred to as the *optimal yield zone*, which extends from the field capacity to the optimal water threshold ( $\theta_p$ ), where the actual evapotranspiration rates are equal to the maximum evapotranspiration rates for a given set of meteorological conditions.

- iii. Finally, the *water stress zone* extends from the optimal soil-water threshold to the wilting point ( $\theta_{WP}$ ), where water is still available to the plants but requires additional energy for extraction.

The sum of these three reservoirs determines the total available soil-water; while the size of these zones varies with crop type and developmental stage, root depth and the crops sensitivity to water stress (Teixeira et al., 1996). The determination of these zone boundaries is critical in estimating the actual evapotranspiration rates. The Penman-Monteith equation and other evapotranspiration calculation methods use these values and estimates of available water in determining actual evapotranspiration. So long as the soil-water is within the optimal zone, the actual evapotranspiration rate can be approximated or assumed to be equivalent to the maximum evapotranspiration  $ET_m$  for the specific crop species determined as (Pereira et al., 2003);

$$ET_m = K_c ET_0 \quad \text{When } R_{max} > R > R_{min} \quad (10)$$

Where,  $ET_0$  is the reference evapotranspiration [mm],  $ET_m$  is the maximum evapotranspiration for the crop species [mm], and  $K_c$  is the crop coefficient [dimensionless].  $R$  is the available water depth [mm], while  $R_{max}$  and  $R_{min}$  correspond to the upper and lower limit of the *optimal yield zone*. Accordingly, the upper limit of the *optimal yield zone* (also the lower limit of the *excess water zone*) corresponds to the available water when the soil-water is at field capacity, given by equation 11; and the

lower limit of the *optimal yield zone* (also the upper limit of the *water stress zone*) is when soil-water is at its minimum, prior to the onset of crop water stress, given by equation 12 (Pereira et al., 2003).

$$R_{\max} = 1000z_r(\theta_{FC} - \theta_{WP}) \quad (11)$$

Where,  $R_{\max}$  is the upper limit of *optimal yield zone* [mm],  $z_r$  is the root depth of crop [mm],  $\theta_{FC}$  is the soil-water content at field capacity [mm/mm], and  $\theta_{WP}$  is the soil-water content at wilting point [mm/mm].

$$R_{\min} = (1 - p)R_{\max} \quad (12)$$

Where,  $R_{\min}$  is the lower limit of *optimal yield zone* [mm] and  $p$  is the soil-water depletion fraction for no stress [mm/mm].

Crop coefficient values used in equation 10 vary over the course of the growing season depending on the stage of the plant. Table 2 lists the crop coefficient values, as reported by the Food and Agriculture Organization (FAO), for four stages in the crop development as well as an overall crop coefficient value for the growing season (Doorenbos and Kassam, 1979). Crop coefficient values in Table 2 are reported as a range; the specific values used in this study is average or mid value of the reported range.

**Table 2.** Crop coefficient values ( $K_c$ ) (Doorenbos and Kassam, 1979).

Crop:	Crop Coefficient Values ( $K_c$ )				
	Initial Growth	Mid-Season	Late Season	Harvest	Overall Growing Season
Bean	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
Cotton	0.7-0.8	1.05-1.25	0.8-0.9	0.65-0.7	0.55-0.75
Groundnut	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Corn, Grain	0.7-0.85	1.05-1.2	0.8-0.95	0.55-0.6	0.75-0.9
Corn, Sweet	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Potato	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Sorghum	0.7-0.75	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soybean	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugar Beet	0.75-0.85	1.05-1.2	0.9-1.0	0.6-0.7	0.8-0.9
Sugar Cane	0.7-1.0	1.0-1.3	0.75-0.8	0.35-0.45	0.75-0.85
Sunflower	0.7-0.8	1.05-1.2	0.7-0.8	0.5-0.6	0.85-1.05
Wheat	0.7-0.8	1.05-1.2	0.65-0.75	0.2-0.25	0.8-0.9

If soil-water is within the stress zone, additional energy is required to extract water, therefore, the actual evapotranspiration ( $ET_a$ ) rate is less than the maximum evapotranspiration rate ( $ET_m$ ) according to equation 77 (Pereira et al., 2003):

$$ET_a = (R / R_{max})ET_m \quad \text{When } R < R_{max} \quad (13)$$

Where,  $ET_a$  is the actual evapotranspiration [mm],  $ET_m$  is the maximum evapotranspiration for the specific plant species [mm],  $R_{max}$  is the upper limit of *optimal yield zone* [mm], and  $R$  is the available water depth [mm], the variation of the available water ( $R$ ) is not linear with time, but follows a parabolic decay curve as water becomes less and less available within the root zone.

The boundary conditions are  $ET_a = ET_m$  when  $R=R_{max}$ , and  $ET_a=0$  when  $R=0$  (Teixeira et al., 1996). Irrigation scheduling is then based on determining the time at which the soil-water content ( $\theta_i$ ), used in the water balance equation, reaches a threshold

soil-water content value. To ensure maximum yield, this occurs when the soil-water reaches the threshold for soil-water content associated with the depletion fraction for no stress ( $\theta_p$ ), when  $\theta_i = \theta_p$  given by Pereira et al. (2003) as;

$$\theta_p = (1 - p)(\theta_{FC} - \theta_{WP}) + \theta_{WP} \quad (14)$$

Where,  $\theta_p$  is the the threshold soil-water content associated with no water stress [mm/mm],  $p$  is the soil-water depletion fraction for no stress [mm/mm] (the fraction of the total available water that can be depleted before water stress occurs),  $\theta_{FC}$  is the soil-water content at field capacity [mm/mm], and  $\theta_{WP}$  is the soil-water content at the wilting point [mm/mm].

In order to reduce risk, the farm manager may wish to schedule irrigations before the soil-water content ( $\theta_i$ ) reaches a predetermined irrigation intervention set point, which is, in this case, set to be the threshold soil-water content ( $\theta_p$ ). This makes irrigation events more frequent and ensures sufficient water to meet demand. However, a managed deficit may be favorable, when irrigation events are scheduled at a point below the threshold soil-water content ( $\theta_p$ ) in order to save on irrigation water cost and conserve water in areas of scarce supply. The resulting reduced yield may be off-set by a more substantial savings in irrigation cost, making the practice more economically favorable. Water supply must be regulated in such a manner as to produce the most economically favorable results. The question for the farm manager is therefore, to determine the soil-water content value at which irrigation events should be scheduled in order to result in the most profitable yields. ISAREG allows for the flexibility in scheduling, but does not

aid in the decision making process by conducting an economic analysis of return at various irrigation scheduling levels.

*CROPWAT Model:*

A similar irrigation scheduling program is CROPWAT, a Visual Basic ® based program, developed by the FAO Land and Water Development Division in order to assist farm managers in determining evapotranspiration rates, crop requirements and irrigation scheduling (Martin, 1992), and is readily available from the FAO website<sup>3</sup>. The program was developed to aid water resource managers in optimizing crop production under conditions of scarce water supply (Smith and Kivumbi, 2002), by predicting the effects of water stress under irrigation deficit conditions, but requires careful calibration of crop parameters and local field conditions.

CROPWAT uses a water balance model that simulates crop water stress conditions to estimate yield reductions based on the determination of crop evapotranspiration and yield responses to water (Allen et al., 1998). In determining the evapotranspiration rate the Penman-Monteith method is used. As discussed previously, this calculation requires climatic data on temperature, humidity, sunshine and wind speed, which is generally maintained by local meteorological service stations.

Daily maximum and minimum temperature values recorded in Celsius degrees are required along with vapor pressure values recorded in millibars (mb), or as a percent relative humidity. Wind speed data must be in units of km/day or m/s for incorporating into CROPWAT. Sunshine values are generally recorded by meteorological stations in units of oktas, but must be converted into a sunshine percentage (*SSP*) as;

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<sup>3</sup> Available on WWW: <http://www.fao.org/ag/agl/aglw/cropwat.htm>

$$SSP = 0.95 - \frac{LC_1 + LC_2}{2} + \alpha \frac{AC_1 + AC_2}{2} \quad (15)$$

Where,  $SSP$  is the sunshine [%],  $LC_1$  is the low clouds at sunrise [oktas],  $LC_2$  is the low clouds at noon [oktas],  $AC_1$  is the high clouds at sunrise [oktas],  $AC_2$  is the high clouds at noon [oktas], and  $\alpha$  is the empirical parameter ( $\approx 0.3$ ) [dimensionless].

Once the necessary data has been tabulated, the data set can be saved and used to calculate the reference evapotranspiration rates ( $ET_0$ ). Following the determination of  $ET_0$  values, crop water requirements can be calculated after entering necessary precipitation and crop data. CROPWAT uses rainfall values for a wet, normal and dry year associated with rainfall values with a 20%, 50% and 80% probability of exceedance. In order to determine these probabilities, past rainfall records for 15 to 30 years are required for calibration. Yearly rainfall totals are calculated and arranged in order of magnitude and ranked accordingly. The plotting position or percent probability is then determined using equation 16 (Martin, 1992). By plotting yearly rainfall values versus the probability of exceedance ( $F_a$ ), rainfall values for a wet, normal and dry year are determined, corresponding to a probability of exceedance of 80%, 50% and 20%.

$$F_a = \frac{100m}{N+1} \quad (16)$$

Where,  $F_a$  is the plotting position [%],  $N$  is the number of records [integer], and  $m$  is the rank number [dimensionless].

Once rainfall data has been entered for a given year, crop characteristics must also be specified. This data includes: crop species and variety, planting date and harvesting date, length of individual growth stages, crop factors relating crop evapotranspiration to  $ET_0$ , rooting depth, allowable depletion levels and yield response factors. Irrigation application is then determined by a simple water balance equation based on soil moisture, allowable depletion and yield response factors (Martin, 1992).

*MARKVAND Decision Support System for Irrigation Scheduling:*

A third example of an irrigation scheduling program currently in use is the MARKVAND, which goes beyond merely scheduling irrigations based on available water, but aids farmers by providing an economic framework in which to make informed irrigation related decisions. MARKVAND is a Danish developed decision support system for irrigation scheduling that incorporates empirical and conceptual models of crop development, water balance and crop yield, with an economic model that prioritizes the crops with respect to their net economic return on irrigation cost (Plauborg et al., 1996). MARKVAND requires daily air temperature, precipitation, and climatic data inputs for estimating potential evapotranspiration calculated using a modified Penman formula. Calculations of plant growth, water deficit, and expected yield deficit, based on reduced water availability, are similar to the calculation methods already presented.

However, what is unique to MARKVAND is its ability to rank crops in need of irrigation, based on the projected economic value increase in situations where multiple crops are being grown on adjacent fields and where water may not be sufficient for all fields. The model is an optimization program for determining water application. The



model aids farmers in prioritizing which fields should receive water, and determining irrigation quantities for each field under scarce water availability. Assuming all crop species suffer the same drought conditions, MARKVAND ranks the crops in order of recommended irrigations, with the first ranked crops resulting in the highest economic return for the recommended irrigation (Plauborg et al., 1996). This allows the farm manager to prioritize irrigation water use for maximum profits and water use efficiency.

### **Optimization of Deficit Irrigation and Irrigation Economics:**

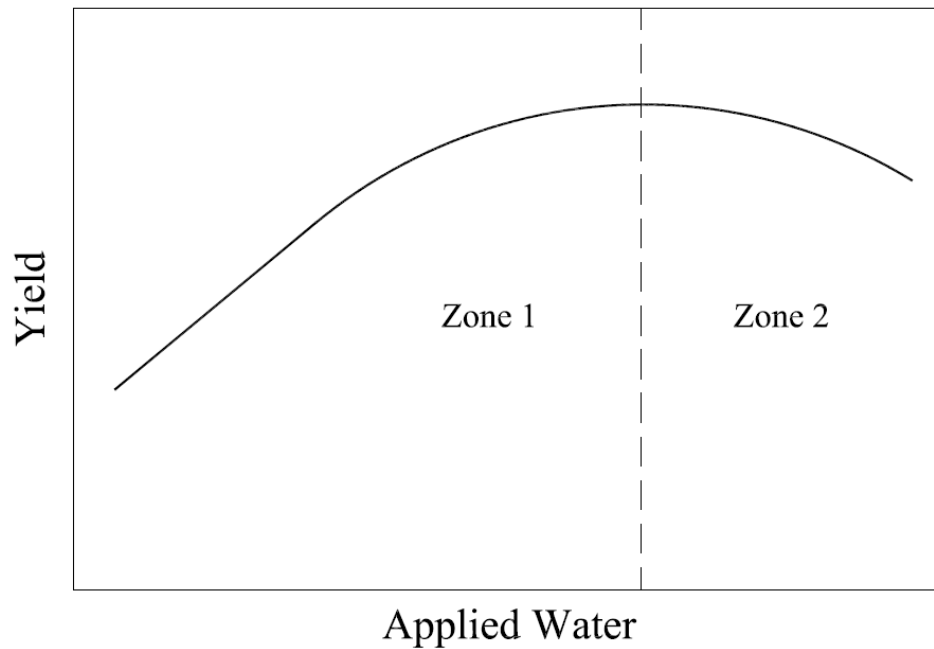
In economic terms, the crop demand should be supplied by applied irrigation water until the marginal benefit, the added profit from increased yields, is equivalent to the marginal cost, which includes the cost of the applied water and the irrigation maintenance costs (James and Lee, 1971). Only in the case where water is free will the irrigation demand required for maximum growth/yield, be equivalent to the applied water quantity associated with the highest economic return. Simply stated, water is to be applied only in the case where the expected return in doing so is greater than the expected cost. James and Lee (1971) present a simplistic relationship between yield and operational costs shown as equation 17. From this relationship the crop water requirement can be determined for maximizing farm income.

$$I = P_c Y - P_w Q_a - V_c Y - F_c \quad (17)$$

Where,  $I$  is the crop water requirement [\$/ha],  $P_c$  is the unit price received for the crop [\$/kg],  $Y$  is the crop yield [kg/ha],  $P_w$  is the cost of water [\$/m<sup>3</sup>],  $Q_a$  is the applied

water [ $\text{m}^3/\text{ha}$ ],  $V_c$  is the variable cost in producing crop [ $\$/\text{kg}$ ], and  $F_c$  is the fixed cost of crop production [ $\$/\text{ha}$ ].

In general, the relationship between crop yield and applied irrigation follows a pattern of rising crop yield with increasing amounts of applied water until an optimal quantity of applied water is obtained, after which yield begins to decrease with further increases in applied water due to over saturation (Mannocchi and Mecarelli, 1994). In general this relationship can be divided into two zones. The first zone corresponds to irrigation deficit practices where applied irrigation is insufficient to result in maximum yields. The second zone indicates a decrease in crop yield as a result of the negative effects of surplus water (Mannocchi and Mecarelli, 1994). This relationship is shown in Figure 10.



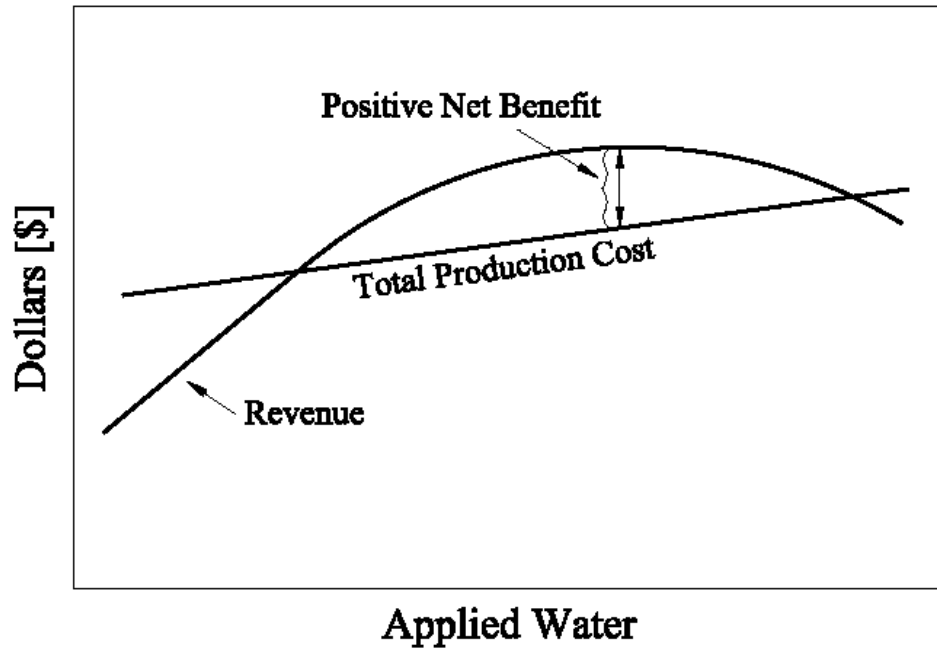
**Figure 10.** Generalized relationship for crop yield to applied water for a generic crop.

Assuming that crop value is constant then the expected revenue is directly proportional to crop yield. This is an important assumption and can be validated if it is assumed that an increase or decrease in yield from a single farm does not significantly affect market supply, and therefore does not affect market price.

From this pattern it is apparent that there is a specific soil-water content at which maximum growth is achieved, however in practice soil-water content cannot be perpetually maintained at a specified point, but rather, varies over a range of values. Nevertheless, by lowering or raising the irrigation intervention point ( $\theta_{min}$ ) and avoiding soil-water over saturation, crop yield can be optimized.

Before determining the value for applied water corresponding to maximum return, data must be collected on the actual and potential evapotranspiration ( $ET_p$  and  $ET_a$ ), crop factors ( $K_c$ ), and actual and maximum yields ( $Y_a$  and  $Y_m$ ). Actual evapotranspiration values can be determined from the water balance equation once a soil-water content time series has been developed.

Assuming revenue is directly proportional to yield, a plot of revenue versus applied water will have the same general pattern determined for a plot of yield versus applied water. From such a relationship it is clear that there is a specific quantity of applied water that will result in maximum revenue. Furthermore, if we assume a linear relationship of irrigation water costs to applied water coupled with the variable and fixed costs of agricultural production, and overlay this expense with expected gross revenue, then the point of maximum net benefit corresponds to a point where the positive difference between revenue and the total cost is greatest (Mannocchi and Mecarelli, 1994). This relationship is shown in Figure 11.



**Figure 11.** General relationship of gross revenue and total cost as a function of applied water for a generic crop.

Due to the linear increase of the total cost of production, the point of applied water associated with the maximum net benefit is just short of the applied water requirement associated with maximum yield. The net benefit value for each unit area is determined using equation 18 (Mannocchi and Mecarelli, 1994).

$$NB = P_s Y_a - \left[ C_0 + (C_1 Y_a) + \left( C_2 \frac{V_a}{EFI} \right) + \left( C_3 \frac{V_a}{EFI} \right) + (C_4 N_w) \right] \quad (18)$$

Where,  $NB$  is the net benefit per unit area [\$/ha],  $P_s$  is the sale price of yield [\$/ton],  $Y_a$  is the actual crop yield [ton/ha],  $C_0$  is the fixed costs of production per unit

area [\$/ha],  $C_1$  is the costs of production varying with crop yield [\$/ton],  $C_2$  is the cost of irrigation water [\$/m<sup>3</sup>],  $C_3$  is the cost of distributing irrigation water [\$/ha],  $C_4$  is the fixed cost of each irrigation [\$/((number·ha))],  $N_w$  is the number of irrigation application events [number], and  $V_a$  is the net available irrigation volume per unit area [m<sup>3</sup>/ha], and  $EFI$  is the total irrigation efficiency. The total irrigation efficiency used in the model, includes the distribution efficiency of the irrigation system selected, combined with efficiency losses as a result of water conveyance or application.

Equation 18 can be simplified by combining the fixed cost ( $C_0$ ), and the cost of production varying with crop yield ( $C_1$ ) (Mannocchi and Mecarelli, 1994). For large productions this may be justified, where the variable cost is less significant when compared to the fixed overall cost of production. The above calculation assumes that crop yield is limited by water supply and that all other inputs, including fertilizers, herbicides and pesticides, have been applied in sufficient quantities to ensure optimal growth conditions. Incorporating these calculations into the determination of irrigation requirements aids in making the best use of limited water resources while maximizing profit.

Irrigation water can be obtained in one of two ways. First water can be retrieved from a groundwater or reservoir source on the farm site, requiring substantial initial investment in pumping stations and piping, but with a minimal subsequent supply cost per unit of water obtained. Secondly, water can be obtained from municipal sources, thereby requiring less initial investment, but exacts a substantially higher cost per volumetric unit of water received. In rural Maryland it is common for landowners to obtain water from wells eliminating the need for extensive statewide water distribution

networks. Withdrawals from such wells or reservoirs are readily permitted, requiring few special considerations. Therefore, for the purposes of this model pumping equipment cost is incorporated into the model for all Maryland sites.

The integration of the economic component of the model will require knowledge of the expected price received by the farmer for various crops, as well as cost estimates of both farm operational inputs and irrigation equipment installations and maintenance. These various costs are likely to fluctuate to some degree from year to year depending on market considerations. Some assumptions of standardized pricing will have to be made in order to simplify the integration of the economic analysis, however, as with small price fluctuations, these assumptions are not expected to significantly impact the effectiveness of the model.

### **Model System Architecture and Integration:**

The Irrigation-Economic tool developed in this study relies upon SWAT output variables in order to determine the optimal irrigation demand and the expected economic return for irrigation installations. The Irrigation-Economic tool, referred to as *IrrigEcon*, is developed in Microsoft Visual Basic ® and is programmed to import data contained within SWAT output files generated at the end of the SWAT simulation. These files contain simulation estimates of actual and potential evapotranspiration rates as well as crop yields at each time step and for each field within the area of interest.

Because the *IrrigEcon* application relies upon SWAT calculations and variables, a thorough understanding of the SWAT model structure, is required in order to properly reference variables used in the *IrrigEcon* application. The paragraphs that follow serve as an introduction to the SWAT program structure, and discuss both the input and output

files used by SWAT, as well as the variables of importance that they contain. These files are referred to in the ‘*Methods and Procedures*’ section of this document, which discusses the implementation of the SWAT model and the creation of required input files.

*GIS Base:*

A geographical information system (GIS) is an integrated technology able to collect, store, manipulate, analyze and present maps and descriptive information about spatially oriented features (Huxhold and Levinsohn, 1995). As a result, geographical information systems have tremendous power and application in research and analysis. Because of their capabilities, GIS software packages are becoming popular and highly utilized tools for consolidating spatial information into a manageable user-friendly format. As the objective of this study is to analyze irrigation requirements over a large heterogeneous terrain, the use of an integrated GIS program to keep track of relevant spatially oriented data is particularly appropriate. This current study involves the incorporation of ArcGIS ®, a GIS software package developed by the Environmental Systems Research Institute (ESRI) that allows the user to incorporate and manage both raster and vector based modules, and allows for menu-oriented integration of SWAT and GIS information.

ArcGIS ® is a collection of tools that allows the user to display, manipulate and create spatially oriented graphical databases. The basic mapping and viewer utility for this application package is ArcView ®, which is commonly available. Much of the functionality of ArcView ® is contained within incorporated utilities, referred to as extensions, which can be turned on or off as needed in order to make the execution of ArcView ® maps more efficient. These extensions can be obtained from ESRI ® or from



third party developers to suit the needs of the user. The ArcView ® interface for SWAT2000, referred to as AVSWAT, is one such extension that can be executed within ArcView ® (Di Luzio et al., 2002). The interface allows the user to load GIS information into the ArcView environment, and then incorporate the data into SWAT files used by the model.

The watershed layout, topography and discretized maps can be incorporated into ArcGIS ® and then applied to the SWAT model, through the use of the SWAT ArcView interface developed at the Blackland Research and Extension Center. The GIS files needed to do this are described in the paragraphs that follow. The use of AVSWAT interface involves the input of both required and optional input maps into an ArcView project prior to the use of SWAT. These thematic maps represent layers of information that include data on elevation, soil type and properties, land use and cover map, hydrographical information including stream lines and water bodies, groundwater, water use, management practices, soil chemistry and water quality. These maps overlay one another in order to provide extensive detailed information on every point within the domain of interest.

However, before discussing the required thematic maps it is necessary to cover some basic information on map data formats and presentation. GIS spatial information is presented in two ways, as either vector data or raster data (Bernhardsen, 2002). Vector models divide the spatial world into clearly defined elements represented by points, lines or polygons. A point is the simplest geographical object represents a single node defined within a two or three dimensional coordinate system (i.e. x, y, and z). A line is a one dimensional object representing a series of points linked over a continuous domain, and

can be straight segments or curved polynomials. A polygon, on the other hand, is a spatially defined plane or shape confined by a set of connected lines.

In contrast, raster data maps divide the mapped area into discrete cells of identical size and assign a single value to each cell. Raster cells are generally square or rectangular, but can be triangular or hexagonal. The amount of detail represented in each raster file is determined by the resolution of the model, which depends on the size of each raster cell.

These data types are important to distinguish, in that they affect the execution of the model. The ArcView-SWAT interface allows for the use of both of these data types, with the exception of the elevation data, which must be in a raster format (Di Luzio et al., 2002). Vector and raster models come in a number of file formats suited for various software applications. The two file formats associated with ArcView ® are referred to as grid and shape files, representing raster and vector data sets, respectively.

Digital elevation data must be imported into ArcView in a grid format, while files containing land cover and soils data can be imported in either a grid format or as a shape file. Stream delineation maps, an optional thematic map used by the AVSWAT interface, must be imported as a polyline-shape file. The paragraphs that follow provide background information on the GIS files used in this project, the sources of information, and any manipulation necessary for use with AVSWAT. Discussion of the use of these files within the GIS-SWAT project is reserved for the *Methods and Procedures* section of this text. The majority of the input information imported into SWAT comes from the GIS files described below.

*GIS Input Files:*

*Elevation Data:* Required format: ArcInfo/ArcView GRID file

There are three required themes that deserve special consideration in the development of the GIS-SWAT project. These include an elevation map, a land cover or land use map, and a soils map. The first of these comes in a special format referred to as a Digital Elevation Model (DEM). DEM data files are digital representations of cartographic information developed by the United States Geological Survey (USGS) as part of the National Mapping Program (USGS, 2004a). DEM files consist of an array of elevations for a number of ground positions in regularly spaced intervals, and are available for sale in 15-minute, 30-minute, and 1-degree units. Small-scale files (7.5-minute) corresponding to a 3-sec arc or 1:250,000 scale are available for the contiguous United States at no charge from the USGS FTP site<sup>4</sup>, which is the scale used in this project.

DEM 7.5-minute files available from USGS FTP site are generally available in a 30x30 meter cell resolution. Each map is approximately a 13.5 km<sup>2</sup> corresponding to a 1/8 degree (7.5-minute) latitude and longitude boundary, and therefore is not seamless. Multiple maps must be synthesized into a single DEM file for evaluation of large areas. This can be done with the use of the 3DEM<sup>5</sup> (version 18.9), a software program freely available for download (Visualization Software, 2004). 7.5-minute DEM files downloaded from the USGS must be identified by state, county and map name. The map name for each quadrangle within the area of interest can be identified using the USGS

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<sup>4</sup> DEM files are WWW available at <http://edc.usgs.gov/geodata/>

<sup>5</sup> 3DEM (version 18.9) software available at <http://www.visualizationsoftware.com/3dem/downloads.html>.

*MapFinder* index<sup>6</sup> (USGS Quads, 2004e). Alternatively, seamless map files can be obtained for larger areas from the USGS Seamless Data Distribution Service<sup>7</sup> for a fee (USGS, 2004b).

DEM file (.dem) is a data format developed by the USGS and must generally be imported and converted for use with the specific GIS software being used. Various GIS software producers have their own standards, file formats and types, which may or may not be compatible with other software applications when data is being transferred from one system to another.

The transfer of files to and from dissimilar GIS software can result in loss of data, therefore, in an attempt to standardize GIS data sets created by the US federal government, spatial elevation maps are being provided in a Spatial Data Transfer Standard (SDTS) format (University of Texas, 2001). SDTS is a standardized distribution format designed for complete content transfer with no information loss, for data transfer between dissimilar computer systems (USGS, 2004). However, these files have to be converted for use in ArcView. A special ‘SDTS Raster to Grid’ conversion utility included with the ArcGIS package is needed to convert these files into a raster grid file format needed by the SWAT-ArcView interface. Directions for the use of this utility are found in the ESRI ArcUser documentation available online<sup>8</sup>.

DEM’s may be used to generate three-dimensional graphics for displaying terrain information. The DEM’s have been used in combination with digital line graphs (DLG’s), digital raster graphics (DRG’s), and digital orthophoto quadrangles (DOQ’s) to create hybrid digital images that enhance visual information. DEM files consist of three

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<sup>6</sup> MapFinder index is WWW available at <http://www.usgsquads.com/>.

<sup>7</sup> Available from the USGS Seamless Data Distribution Service at: <http://seamless.usgs.gov/>

<sup>8</sup> Available WWW: <http://www.esri.com/news/arcuser/0100/webdata8.html>

record types: 'A,' 'B' and 'C' (USGS, 2004). The type 'A' record states general characteristics of the DEM file including: name, boundaries, units of measurement, maximum and minimum elevations, and the number of 'B' records. 'B' records contain profiles of elevation data and associated header information. 'C' records contain statistical information on the accuracy of the data.

*Land Cover/Land Use File:* Required format: ArcInfo/ArcView GRID or Shape file

Information on land use and land cover is available from the Maryland Department of Planning (MDP, 2004)<sup>9</sup>, or from the USGS National Land Cover Database (USGS, 2004d)<sup>10</sup>. The GIS files used in this project are obtained from the USGS National Land Cover Database (NLCD) as these maps are more comprehensive and detailed with regards to the vegetative cover and land use throughout the area. These files are available in TIFF format which can be readily converted into the required grid format with a 30x30 meter resolution. NLCD data files are based on a 21-class land cover classification scheme, and are available for all areas throughout the United States. The classification scheme is based on the Anderson land-use and land-cover classification system, and therefore must be reclassified according to the scheme used by SWAT. The reclassification scheme and procedure used is discussed in the *Methods and Procedures* section of this report.

*Soils Data:* Required format: ArcInfo/ArcView GRID or Shape file

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<sup>9</sup> Available WWW: [http://www.mdp.state.md.us/zip\\_downloads.htm](http://www.mdp.state.md.us/zip_downloads.htm)

<sup>10</sup> Available WWW: <http://landcover.usgs.gov/natl/landcover.asp>

State soils data is obtained from the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA)<sup>11</sup>. Three soils geographic datasets are maintained by the NRCS and include: the Soil Survey Geographic (SSURGO) database, the State Soil Geographic (STATSGO), and the National Soil Geography (NATSGO) database (USDA, 19995). Each of the three datasets contains varying levels of detail appropriate for local, state and national scales. The SSURGO dataset provides the most detailed information appropriate for model scales ranging from the farm/ranch level to the county level. The STATSGO and NATSGO datasets contain less detailed information appropriate for maps as the state or national level modeling, respectively. The STATSGO dataset is used in this study, as the level of detail contained therein is most appropriate for the scale of the Pocomoke basin of interest.

*NHD Stream Network File:* Required format: ArcInfo/ArcView Polyline Shape file

The National Hydrography Dataset (NHD) stream delineation file is distributed by the USGS, and can be obtained for any area within the United States as polyline shape files, available from the NHD website<sup>12</sup> (USGS, 2004c). The National Hydrography Dataset is the result of a joint effort of the USGS and the Environmental Protection Agency (EPA) to combine EPA Reach files (version 3) and USGS digital line graph (DLG) hydrography files into a single reference (USGS, 2000). The USGS provides NHD files in bundled packages associated with each hydrologic cataloging unit.

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<sup>11</sup> Available WWW: <http://soildatamart.nrcs.usda.gov>

<sup>12</sup> Available WWW: <http://nhd.usgs.gov/data.html>

The use of the NHD stream delineation file is optional in SWAT, but aids in the delineation of exact stream locations. SWAT is capable of calculating estimated stream positions with the use of an elevation grid file alone, however, the limited resolution of the file, particularly with low lying flat areas, makes the incorporation of the NHD stream delineation of added advantage.

*SWAT Input Files:*

Most of the spatial data required for the execution of SWAT is contained within the GIS files described above, and is incorporated into the model files through the use of the ArcView-SWAT interface. The paragraphs that follow describe the structure of the SWAT model and the files used during model execution, as well as the input information required.

The full functioning of SWAT requires a tremendous amount of input data that must be carefully formatted and is contained within 30 separate input files. These files contain information on climatic variables, hydrological cycle components, sediments, nutrient concentrations, pesticide use, bacterial presence, plant and crop properties, management practices, channel processes and impoundment processes (Neitsch et al., 2002b). As the study here is concerned primarily with only a portion of the functionality of the SWAT model, discussion will center on the data collection and input of data required for the hydrological, climatic and growth model components of SWAT, which are essential in the determination of irrigation schedules. Other model optional inputs is discussed only briefly in order to provide a general overview of the model components.

The user can differentiate the input files as watershed files, containing input information pertaining to the entire watershed, or as subbasin and HRU files, which

contain information concerning the sub-watersheds contained within the area of interest. The input files containing information most pertinent to the hydrological, growth and climatic components of the model are described below, a fuller description can be found in the SWAT user manual (Neitsch et al., 2002b).

Many of these files are created using the SWAT-ArcView interface that obtains information already incorporated into an ArcView ® project (Di Luzio et al., 2002). The incorporation of input data and the procedure for developing necessary input files from the ArcView project is discussed further in this text. The following paragraphs describe files used in SWAT and specific options or procedures associated with each file, as used in this study.

The configuration file (.FIG):

The watershed configuration file defines the routing network of the watershed. The configuration file is used to route the stream loadings and add flows through the watershed. SWAT uses this configuration to discretize the watershed and to define the relative position of the subbasins and HRU units. The discretization of the watershed is the first step in the model development procedure. SWAT allows for three discretization processes, which divide the watershed by grid cells, representative hill slopes, or subwatersheds, each of which have strengths and weaknesses. Division of the watershed into subwatersheds is the approach used in this study, which best accommodates the calculation of hydrographic information.

The control input/output file (file.CIO):



This file contains the name of all input/output files used in the simulation, including files containing specific information pertinent to each subbasin, and to the watershed as a whole, as well as all climatic data files used. The naming scheme of the files is left up to the individual user, and therefore must be carefully documented in the control file. However, due to the complexity of the program and the number of input/output files involved the file extensions are maintained in order to determine the type of information contained within each file.

The input control code file (.COD):

The input code file (.cod) defines which processes are modeled by SWAT and governs the general operation of the model. This file includes start and end dates, duration, time-steps, and data output or printing frequency. As indicated in the introductory material of this report, SWAT is capable of reading actual input data used in the simulation or is capable of generating climatic input data based on historical numbers. The code file (.cod) defines which climatic variables are generated and which are read directly from an input file.

Those parameters in which SWAT can either generate values, or read actual data from an input file source include: temperature, solar radiation, relative humidity, and wind speed (Neitsch et al., 2002b). Assigning a value of 1 or 2 instructs SWAT to use measured data read for each subbasin, or simulated data generated for each subbasin, respectively. In all model simulations conducted in this study weather data is generated based on historical data. In the code file the user is also able to specify which method of

calculation is used, in cases where more than one method is possible, such as with the determination of potential evapotranspiration and infiltration calculations.

The basin input file (.BSN):

The general watershed attributes are defined in the basin input file. This file defines a wide range of input parameters including watershed area; parameters involved with snowfall and snow melt; nitrogen concentration in rainwater; runoff factors; initial soil-water storage; nitrogen/phosphorus uptake and distribution, percolation, partitioning and availability; and bacterial growth, presence and die-off.

The general input files (.SUB and .HRU):

The subbasin general input file (.SUB) contains information related to tributary channel properties, topography, climate change variables, and the names of the HRU input files (.HRU) used in the simulation. The HRU input files contain information on HRU area, surface and subsurface flow, irrigation, tile drains, and parameters affecting erosion.

The weather generator input file (.WGN) and climatic record files:

The weather generator input file contains the statistical data needed to generate daily climate data, ideally at least 20 years of records are used to calculate these parameters. The file contains average daily precipitation, maximum and minimum daily temperatures, solar radiation, wind speed and relative humidity values, as well as standard deviation values for the above parameters, and probability factors used in

weather station calculations. The weather generator simulates climatic data when the user specifies that climatic data should be generated or when there is missing data in the measured data files.

Measured precipitation data is contained within a series of data files, up to 18 files, capable of holding records from multiple gauging stations. The precipitation file (.PCP) is formatted to contain daily or sub-daily precipitation records depending on whether the SCS curve number method or the Green and Ampt method of calculating runoff and infiltration is used. In the case of this study, where the SCS curve number method is used to calculate surface runoff, only daily precipitation values are incorporated into the model. The precipitation file must contain records for the entire period of the simulation, for those days where a record is missing a value of (-99) is entered and SWAT will automatically generate a simulated value. This cannot be done in the case where SWAT is simulating all values based on historical data, as done in all simulations conducted in this study.

The temperature input files (.TMP) contain maximum and minimum air temperature values for the duration of the simulation. Like the precipitation input data SWAT can utilize up to 18 temperature files, capable of holding information from multiple gauging stations. One solar radiation file can be used in the simulation, which can contain data from multiple gages. Wind and humidity records are both needed when the Penman-Monteith method is used to calculate potential evapotranspiration, which is done in this simulation. These values are contained within the .WND and .HMD input files, respectively. Only one of each of these files can be used for each simulation.

The HRU management file (.MGT):

The HRU management file contains information needed to assess the impact of management activities on a given system. This file contains variables related to planting, harvesting, irrigation application, nutrient and pesticide application, and tillage operations. Altogether SWAT can simulate 14 different types of management operations the most important of which, for the purposes of this project, is irrigation. This will allow the user to run multiple executions of the simulation, for fields with and without irrigation. For comparison purposes, SWAT allows the user to simulate periodic user specified irrigation event or auto-irrigation events, and to specify the exact source of the irrigation water including any reservoir or stream from within the modeled area or from outside of the area of interest.

The consumptive water use file (.WUS):

This file specifies daily removal rates of water used for consumptive urban and industrial use exported outside of the watershed being modeled. The water consumed is considered to be lost from the system. This is an optional file not used in this study, but can be incorporated if water withdrawals are likely to affect plant water availability.

The soils data input files (.SOL and .CHM):

The input soils data includes physical and chemical characteristics of the soils within each HRU. The values for the physical characteristics of the soil is contained within the soils input file (.SOL), and is essential in the determination of the water movement through the soil profile. The chemical characteristic values of the soil profile

are contained within the soil chemical characteristics file (.CHM) and are used to set the initial levels of nutrients and pesticides within the soil profile. The physical properties input file is required by SWAT, while the chemical inputs file is not. Default soil variable values are provided by the STATSGO soils data used in this study.

The groundwater input file (.GW):

The groundwater input file includes all properties that govern the movement of water into and out of the aquifers. SWAT divides the groundwater supply into two aquifer systems, the unconfined aquifer, which contributes to return flow to streams within the watershed, and the confined aquifer, which contributes return flow to streams outside of the watershed.

The main channel input file (.RTE):

The main channel input file contains information regarding the physical characteristics of the channel network within each subbasin, including channel width, slope, depth, Manning's roughness, hydraulic conductivity, erodibility and channel cover. Many of these variables are not critical in determining soil-water content, and therefore are of little significance to this project.

The water quality input files (.WWQ, .SWQ and .LWQ):

Water quality information is incorporated into three files used by SWAT, the general water quality input file (.WWQ), the stream water quality input file (.SWQ), and the lake water quality file (.LWQ). These files contain information affecting processes

concerned with nutrient, pesticide and sediment levels in the main channels and reservoirs. These are optional files not needed for the operation of SWAT. These instream processes are not modeled in the current study, and therefore, have not been incorporated into the model.

The reservoirs and impoundment input file (.PND and .RES):

Parameter values needed to model water, sediment and nutrient balances within reservoirs and impoundments, including wetlands and ponds located within the subbasin, are contained within the reservoir input file (.RES) and the impoundment input file (.PND), respectively. These are optional files in SWAT and not included in this study.

Crop growth and land use data files (.DAT):

Five database files are used to store information concerning land cover/plant growth, tillage, fertilizer components, pesticide properties and urban land characteristics. These database files are distributed with SWAT and include standard information for a variety of common plant species, tillage practices, and fertilizers and pesticides used. These files can be expanded to include information on special plant species, and agricultural inputs and practices not included with the standard dataset.

The CROP.DAT file contains information needed to determine plant growth, yields, optimal temperature conditions, leaf area index, canopy height, rooting depth, stomatal resistance and the like. For plant species not included in the CROP.DAT file additional information for other plant species can be entered if available, however, the

physical based properties of special plants may require field validation, which may be difficult to obtain or perform.

The TILL.DAT file contains information needed to model tillage operations that serve to redistribute nutrients, pesticides and plant residue within the soil profile depending on the type of tillage operation being conducted. The PEST.DAT file contains information regarding pesticide fate and transport for commonly used pesticides. The FERT. DAT file contains information on nitrogen and phosphorus ratios in various commercially available fertilizers, it also contains information on bacteria levels in applied manure. Finally, the URBAN.DAT summarizes parameters used to simulate different types of urban areas.

Of these five database files the crop/land cover database containing information on plant growth is most critical to irrigation scheduling. The details of the other four standard databases are not included in this report, as the variables they contain are not critical in the development and execution of the irrigation scheduling program; however, a full explanation of these databases can be found in the SWAT user manual (Neitsch et al., 2002b).

The land cover/plant growth database contains details on variables related to plant growth under ideal conditions and the impact of various stresses on plant growth. Included within the internal SWAT standard database is 79 of the most economically important crop species, and plants commonly found within the general landscape, as well as 18 generic land cover categories, included in order to provide rough estimates of plant parameters for mixed coverage or species not already specified in the database. A list of the plant species and generic land cover categories, included in the SWAT standard

database, is contained in Appendix C of this report. The list of these species is taken from the SWAT user manual (Neitsch et al., 2002b), which includes specific variable values for each plant species, and provides guidance on how to measure the variables associated with each plant species for species not included in the standard database.

The physical variables included in the database for each crop species, account for variables used in the equations related to temperature response, leaf area development, biomass conversion, canopy height, root development, plant nutritional content, and harvest and yield response. A summary of pertinent variables included is presented below, and a complete list of the plant variables is included in Appendix C. The variable codes used in the development of the irrigation program are also included within the tables of Appendix C, as well as a description of significant parameters.

*SWAT Output Files:*

During the SWAT model execution this input information is integrated and used to determine specific output values contained within a series of output files. The SWAT simulation results in the generation of four principal output data files (Neitsch et al., 2002b), which include: a summary output file (output.std), the HRU output file (.sbs), the subbasin output file (.bsb), and the output files associated with the main reach (.rch) or water bodies present. These files organize generated output data for four summary categories representing the overall watershed, the individual subbasins, the HRU's within each subbasin, and the main reach and other water body elements, respectively. The summary information included in these files is generated based on the time step and calculation parameters selected during the initial setup of the SWAT simulation.



Of primary concern in the execution of this project is the HRU output file (.sbs), which presents summary information on evapotranspiration values, cumulative precipitation, soil-water content, and loadings for each HRU, with values generated for each time step over the span of the simulation. These values are critical in the determination of irrigation schedules. The variables taken from these database files, and used in the development or execution of the Visual Basic ® irrigation program, are included in Appendix E. The tables included in this appendix list the sources of the data used in the irrigation program, as well as the program variable names.

The subbasin output file (.bsb) contains similar information to that of the HRU output file, summarized for the individual subbasins within the watershed. The summary output file (output.std) contains nutrient, sediment and pesticide loadings for the entire watershed modeled, while the main channel (.rch), impoundment (.wtr), and reservoir (.rsv) output files contain loadings and in stream process variables associated with each water source. These values are not significant in the determination of irrigation schedules, and therefore, are not used in the irrigation prescription portion of this project, but are relevant when determining the environmental impact of irrigation, as will be discussed further in this text.

### **CHAPTER III: OBJECTIVES:**

The overall goal of this study is to create an irrigation economic application that is able to determine if irrigation installations are profitable for a number of agricultural fields within a specified area of interest, and to determine the optimal water demand, based on soil properties, subsurface hydrology, meteorological data, agricultural practices, crop type, and the net economic return on irrigation investments. In order to achieve this goal the following were my objectives:

1. Develop a GIS database for the Pocomoke river basin located within Maryland's eastern shore, including all required data with regards to land use, slopes and elevations, soil properties, soil layer depths, existing aquifers and surface water bodies, and crop type characteristics, including crop evapotranspiration coefficients, yield response coefficients, maximum rooting depth, and planting and harvesting dates.
2. Apply the SWAT model (Soil Water Assessment Tool) to the defined area of interest, in order to determine hydraulic and plant growth variables needed by the irrigation economic decision support system, and assess yield values with and without irrigation.
3. Develop and program the irrigation economic application to estimate the net benefit of irrigation installations for each field defined within the area of interest, and estimate the average optimal irrigation volume to be applied given the data incorporated into the SWAT model. The economic component

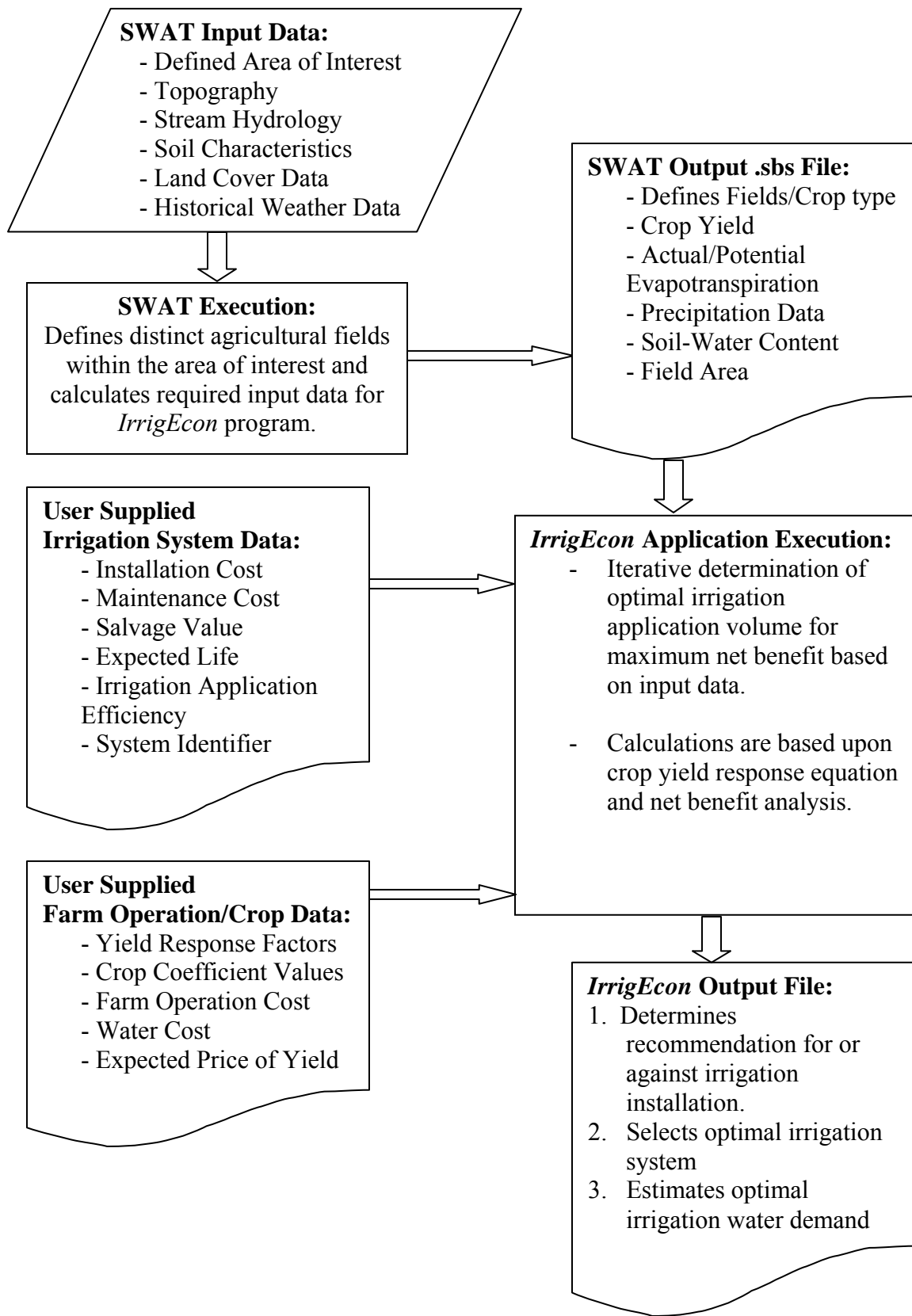
of the application evaluates and balances the capital and variable costs of applying irrigation water to agricultural fields against the expected yield increase associated with the supplemental irrigation in order to determine the optimal irrigation system and applied water volume required for maximum profit, taking into consideration the irrigation efficiency of the irrigation systems evaluated.

4. Use the irrigation economic tool to identify fields associated with the greatest potential net benefit with irrigation installations and to characterize and differentiate between these fields based on relevant input data.
6. Evaluate the environmental impact of supplemental irrigation on non-point source pollution from agricultural fields over a range of irrigation intensities using the SWAT model.

## **CHAPTER IV: METHODS AND PROCEDURES:**

### **General Overview:**

The specific contribution of this study was the development of a program, referred to as *IrrigEcon*, capable of determining the potential net benefit of proposed irrigation systems on multiple and diverse agricultural fields within a given area of interest; and to make recommendations as to the value of irrigation installations and the type of installation best suited for a given field. Figure 12 presents a schematic of the components of the *IrrigEcon* model as well as the general input requirements. The section that follows details the determination of the input data within SWAT, and the development and execution of the *IrrigEcon* model.



**Figure 12.** General overview of the *IrrigEcon* model and required input data.

The *IrrigEcon* application relies upon three primary sources of information. The first is the SWAT output file (.sbs file) which defines the fields within the area of interest that contain agricultural crops and provides information on crop yields and actual/potential evapotranspiration values over the course of the simulation. SWAT itself requires input data defining soil properties, crop properties, and historical weather data. The second input requirement is information specific to the irrigation systems under consideration contained within a text file. This file includes information on irrigation installation cost, maintenance cost, salvage cost, expected life of the system and water distribution efficiency, which will generally have to be estimated based on supplier information and construction estimates. The final source of information summarizes required farm operation data in a text file, and includes data on farm operational costs, the expected price received for the crop, the cost of water, the crop coefficient and the crop response factor.

It is important to note that, for the purposes of this study, the *IrrigEcon* application is programmed to accept the specific format of the SWAT output .sbs file as the sole source of input for all crop yield, and evapotranspiration values for the defined agricultural fields within the area of interest; however, with slight modifications to the *IrrigEcon* application code, the program can be designed to accept input data from alternate simulation models or user compiled data. In this way, SWAT is used only as a tool for generating required input data, but can be replaced if alternate data is obtained.

Secondly, the purpose of this study is not to develop an application to aid in developing an irrigation schedule, as multiple software packages exist to aid in this effort.

Rather the specific contribution of the current study is to provide a program that will: first, make recommendations for or against irrigation installation, based on crop growth and economic factors, particularly in temperate zones where the necessity of irrigation is not clear; secondly, to select the irrigation system that will be most profitable based on a cost analysis and performance of each system; and thirdly, to provide an estimate as to the optimal water demand based on the expected return in yield and cost inputs.

From the data obtained individual farm managers may assess where irrigation installation might result in the greatest profit. On a wider scale water resource managers and regional policy makers may be able to use this model to better assess the economic value of applying water to agricultural production, and more informatively, assess the needs of agriculture in contrast to other sectors of society. They could thereby be able to more intelligently justify the allocation of water resources to each sector of society.

### **SWAT Simulation Development and Execution:**

The initial thrust of the work involves acquiring relevant data and processing the GIS information prior to incorporation into the SWAT model. The processes outlined below discuss the tools used, and the digital maps and data acquired. Although a great deal of preliminary work involving data acquisition, formatting and processing, is required prior to the execution of the steps below, the sources of digital information and the formatting required are discussed while outlining the steps in the SWAT model development in which the digital GIS information is used.

The scope of the simulation is conducted at the watershed scale using the Pocomoke river basin as the modeled area. The Pocomoke watershed is considered a

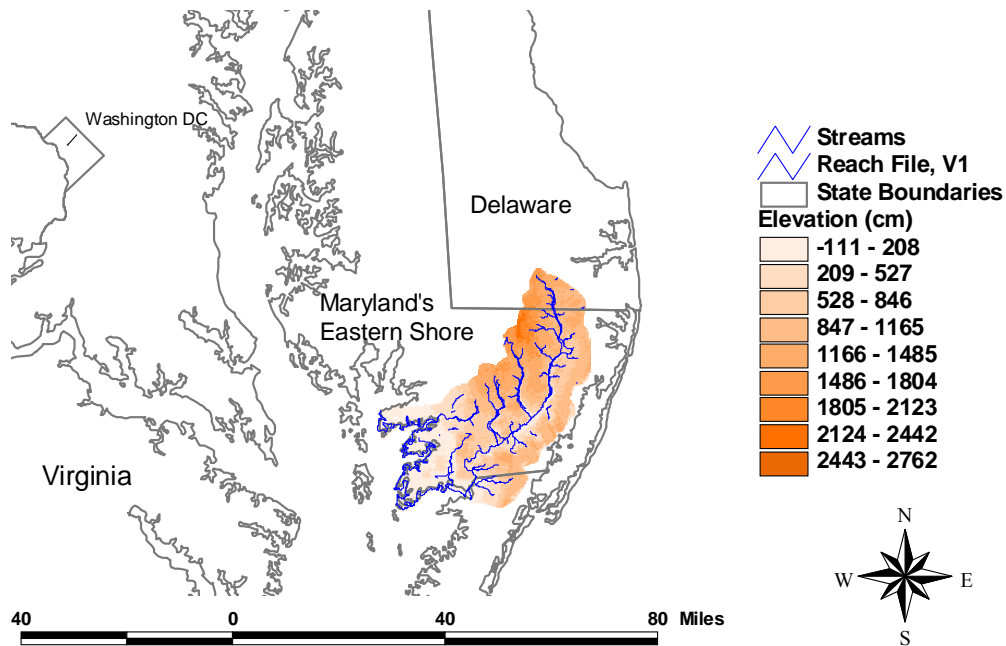
representative watershed within Maryland's eastern shore, extending from the lower limits of Maryland's eastern shore, protruding slightly into Virginia and extending northward into parts of Delaware (Figure 13). The paragraphs that follow explain the general procedure used in each simulation and the data incorporated into each run.

*Watershed Delineation:*

The initial step in the development of the input files for the SWAT model is the delineation of the watershed into discrete adjoining subbasins that comprise the overall watershed or area of interest. The USGS has developed a system of delineating parcels of land, associated with river basins, based on the scale at which US rivers are viewed (EPA, 2004c). The system is comprised of a nested hierarchy that divides the United States into regions, subregions, accounting units, and cataloging units. Cataloging units are assigned a unique 8-digit code, which is the concatenation of 4 pairs of double digit number codes associated with each of the higher division classifications. The Pocomoke watershed, modeled in this study, is identified by the cataloging unit number 02060009, as classified by the USGS (EPA, 2004c). Figure 13 shows the extents and relative location of the Pocomoke watershed within overall Delmarva region.



# Location of Pocomoke Watershed



**Figure 13.** Relative location and elevation grid of the Pocomoke watershed.

The cataloging units are further divided into subwatersheds, varying in size according to circumstances of the site and the scale at which these areas are viewed. Generally, spatial digital information is made available for each cataloging unit. Digital information on rivers and streams, land use, elevations, and soil types can be obtained from various governmental organizations for each hydrological cataloging unit.

The first step in the watershed delineation process subdivides the modeling area, into smaller hydrological units. The delineation tool requires that only the digital elevation map be used, but has the option of using a mask to define the area of interest, and a digitized stream polyline shapefile, to define the exact location of streams and

channel reaches. Although not required, the mask and stream files help to increase the efficiency of the model calculations and to improve the accuracy of the watershed delineation process, and for this reason have been included in this model.

#### Map Projection:

The delineation and subdivision of the watershed of interest requires that relevant GIS data be imported into an ArcView project. When the data is imported, a projection or framework for the imported data must be defined. Projections are mathematical formulations that allow a three-dimensional spherical surface to be represented on a flat two-dimensional plane (EPA, 2004a). Although all projections distort the image's shape, area, distance and/or direction, the degree of distortion varies with the scale, region of the map, and the projection being used. The projection used for images incorporated into this project is the 'State Plane – 1983: Maryland' which is the most recently standardized statewide projection format, intended to cause minimal distortion for maps of Maryland. The Maryland state plane parameters are based on the North American Datum reference of 1983.

Because projections position, orient and distort images in different ways it is critical that all thematic layers and files used in the ArcView project have the same projection, in order that they overlay each other exactly, allowing each point of a distinct layer to correspond to mirrored points on other map layers. The projection also defines the spatial coordinates and orientation of the image. The central meridian and the reference latitude correspond to a central point within Maryland and, therefore, minimize distortions associated with maps of Maryland. For this reason all maps used in this study

are projected using the Maryland state plane projection. Using the Maryland state plane projection minimizes these distortions for the area of interest in this study. The details of the Maryland state plane projection are listed below. Points closest to the central meridian and the reference latitude, expressed in decimal degrees, are distorted least on the two-dimensional projection; points further out have greater distortions, although relatively insignificant.

Details of Maryland state plane (1983) projection:

Projection: State Plane - 1983; Maryland

Spheroid: GRS 80

Central Meridian: -77

Reference Latitude: 37.6667

Standard Parallel 1: 38.3 (lower boundary)

Standard Parallel 2: 39.45 (upper boundary)

Stream Processing and Delineation:

Elevation grids used in this study were obtained from the USGS National Elevation Dataset (NED) available online<sup>13</sup> (USGS, 2004c). The USGS provides NED data for the United States in a raster format at a 30x30-meter resolution. After selecting the digital elevation grid, the next step is to define the area of interest for the simulation. In this case a mask of the Pocomoke watershed is created from a shapefile of all hydrological cataloging units within the United States made available by the USGS (NationalAtlas.gov, 2004).

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<sup>13</sup> Elevation data grids can be downloaded from <http://ned.usgs.gov/>

The use of a mask grid is an optional procedure, incorporated into the model only to increase the efficiency of the modeling process. By limiting the focus area of the model to the region of the imported mask, SWAT computations are conducted only on the specific area of interest, thereby reducing the processing time by limiting its area of operation.

AVSWAT utilizes the ArcView *Spatial Analyst* and *Dialog Designer* tools in order to calculate the location of streams throughout the watershed based on topographic information provided by the USGS elevation map. In order to increase the efficiency and accuracy of the process, SWAT allows for the option of uploading a polyline shapefile delineating the stream network for the area of interest, which is superimposed onto the elevation map (EPA, 2004a).

The option of using a stream network shapefile is selected for this project, and allows for more accurate stream definition. This feature is especially useful in cases where the elevation map does not contain sufficient detail to accurately predict the location of streams based on topography alone. This is particularly true of Maryland's eastern shore, where extensive areas of coastal flat land may make stream delineation and flow variable calculations difficult, when digital elevation models of limited resolution are used.

In this case the stream network file provided by the National Hydrography Dataset (NHD) is used during the SWAT project development. The NHD GIS data are distributed by the USGS<sup>14</sup>, and can be obtained for any area within the United States as polyline shape files. NHD files are the result of a joint effort of the USGS and the EPA to combine EPA Reach File (version 3) and USGS Digital Line Graphs (DLG)

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<sup>14</sup> Available on WWW: <http://nhd.usgs.gov/data.html>

hydrography files into a single reference (USGS, 2004c). The USGS provides NHD files in bundled packages associated with each hydrologic cataloging unit. In the case where multiple NHD files are needed, the individual shape files are merged into a single theme labeled 'digitized streams.' The resulting digitized stream theme is then edited directly within ArcView to ensure the connectivity of the stream network.

In the case where a NHD file is used, an accompanying flow direction table (in dBase format) must be provided indicating the flow direction of each stream. NHD files are filtered to a limited degree by SWAT in order to eliminate areas of standing water or no flow areas, referred to as 'sinks.' SWAT uses the flow direction table to process the NHD file in order to create a new ArcView theme of stream locations. During this process SWAT will eliminate what it sees to be lakes and reservoirs or areas of standing water. As a result, the continuity of the stream network may be affected. This requires that the stream network be manually edited to ensure connectivity, by drawing connective lines through lakes and reservoirs, and connecting disconnected reach segments. This stream delineation editing process is done directly within the SWAT-ArcView interface, and the newly edited stream network map is then used in the watershed delineation process.

#### Subwatershed Delineation, Definition of Threshold Area:

Once the map elevation, the masked area of interest, and the stream network files have been imported and processed, the boundaries of the subbasins are defined. This requires the input of a threshold area, which defines the drainage area used to determine the distribution of subbasins within the area of interest. The threshold area value is an

indication of the resolution of the stream network. The smaller the value the more detailed the stream network, i.e. the greater the number of drainage areas or subbasins calculated. AVSWAT also uses this value in processing of the NED map in order to define the density of the stream network.

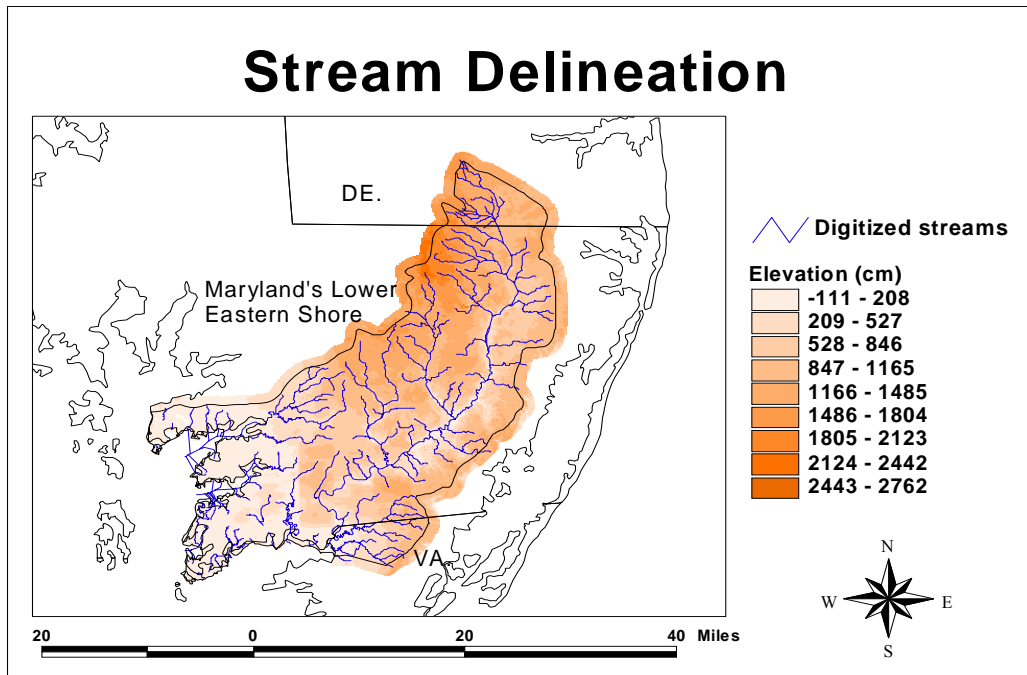
Given the user specified threshold area, SWAT determines the location of each outlet point, for each calculated subwatershed along the stream network. Additional outlets can be added or removed by the user and set at specific locations at the end of the process. After numerous trials it has been found that the best approach to watershed delineation is to select a relatively small threshold area, and then remove and redefine the location and number of the calculated outlet points. This approach tends to lead to the best results, in terms of continuous coverage area, although it is the most labor intensive. Specifying a larger threshold area limits the number of subwatersheds calculated, resulting in a more manageable number, however, the resulting coverage area tends to be disjointed, specifically at the coastline and in low lying wetland areas.

There seem to be two reasons for this. First, the coastal areas used in this study are relatively flat, with much of the land area at or near sea level, having considerable wetland coverage. As a result of the limited resolution of the elevation spatial data, the watershed delineation tool may not accurately determine the drainage patterns of areas with nearly equivalent elevation (i.e. flat coastal areas at sea level), thereby leaving patches of land that are not accounted for in the resulting subwatershed discretization. In these instances SWAT defines these area, where water does not drain easily, as sinks and then eliminates these areas during the subbasin discretization process.

Secondly, small coastal patches of land, less than the specified minimum threshold size, draining directly into the bay or small tributaries, are not accounted for during the subbasin discretization process, as a channel stream for these small areas is not calculated, since the surface water is hydrologically isolated from the closest calculated reach outlet point. A more manual delineation approach helps to minimize these problems.

This procedure results in a more complete coverage area, although the variability of the subwatershed area may vary over a wider range. The increased variance is due to the fact that the location of some of the subwatershed outlets are visually positioned within the area of interest, rather than solely computer calculated. This may lead to subwatersheds of greater or lesser size when compared to the variance in subwatershed size calculated automatically with the subwatershed delineation tool.

Following the completion of the delineation process a *Topographic Report* is generated providing a statistical summary and detailed information regarding the distribution of land surface elevations within the overall watershed and within all subwatershed divisions. Figure 14 maps the stream delineation for the Pocomoke river basin showing both the topographical map and incorporated channel location.



**Figure 14.** Stream network and topographical map of the Pocomoke river basin.

*Land Use and Soil Classification:*

The next step in the data preparation process is to import and overlay the land use and soils classification grids. This is done using the *Land Use and Soil Classification* tool embedded within the ArcView-SWAT interface program. Through the use of this module the soil and land use GIS data required by SWAT is loaded and processed in order to determine the area and the hydrological parameters for each land use-soil category simulated within each subwatershed. Both the land use and soil themes are projected using the Maryland state plane parameters prior to the execution of the *Land Use and Soil Classification* tool.

AVSWAT allows GIS land use and soil themes to be imported as either shape files or grid files, however shapefiles are automatically converted into grid files, which is



the required format of the *Spatial Analyst* extension used in the process. In this study land use files are imported as preformatted grid files, while soil data maps are imported as shape files. The preparation of the land use grid file requires that the grid cell size resolution and the map extents be the same as that of other grid files used in the simulation, specifically the elevation map and the mask files.

The land use file used is downloaded from the *National Land Cover Database* in an initial TIFF format maintained by the USGS<sup>15</sup>, which is described in the introductory material of this report. This map broadly defines areas of agricultural production, but does not specify individual parcels of land with specific crop types, but rather broadly classifies all agricultural row-crop with a single label.

Once the landuse data is obtained for the area of interest, the soils dataset is obtained from the STATSGO dataset, which is provided by the USDA, which broadly classifies soils data for modeling at the regional or statewide scale. For the purposes of this project, landuse and soils data was obtained for Maryland, Virginia and Delaware was merged and then cropped for the area extents considered in this study in consideration of the fact that the Pocomoke watershed extends through parts of all three states. This work was done using the map calculating tools incorporated into the ArcView package prior to the development and use of the SWAT model.

Once the necessary data files have been prepared the *Land Use and Soil Classification* tool imports the land use and soil themes selected by the user and overlays one on top of the other in order to identify unique combinations of landuse and soil type, which identify and define the individual HRUs within each subwatershed. Each HRU

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<sup>15</sup> Land use data is available on the WWW from the USGS National Land Cover Characterization: <http://landcover.usgs.gov/natl/landcover.asp>.

<sup>17</sup> A full description of NLCD codes can be found at <http://landcover.usgs.gov/classes.asp>

represents one land use-soil combination, and has a unique set of hydrological parameters and physical variables associated with it; values that are later used during the execution of the SWAT model.

During this process the landuse and soil maps must be linked to the landuse and soils database maintained within the SWAT program, which includes all of the required physical and chemical values associated with each land use and soil type used during modeling calculations. In order to do this the land use and soils data provided must be reclassified or linked to the codes used in the SWAT model, in order to access necessary database information contained within the SWAT program. This is done through the use of a lookup table that links the landuse and soil descriptions, included in the attributes table of the landuse and soils GIS files, with the databases codes used by SWAT.

The built in lookup table already incorporated into the SWAT model is used to reclassify the STATSGO soils data. However, a specially tailored lookup is needed for reclassifying landuse data provided by the *National Land Cover Database*, the details of which are shown in Table 3.

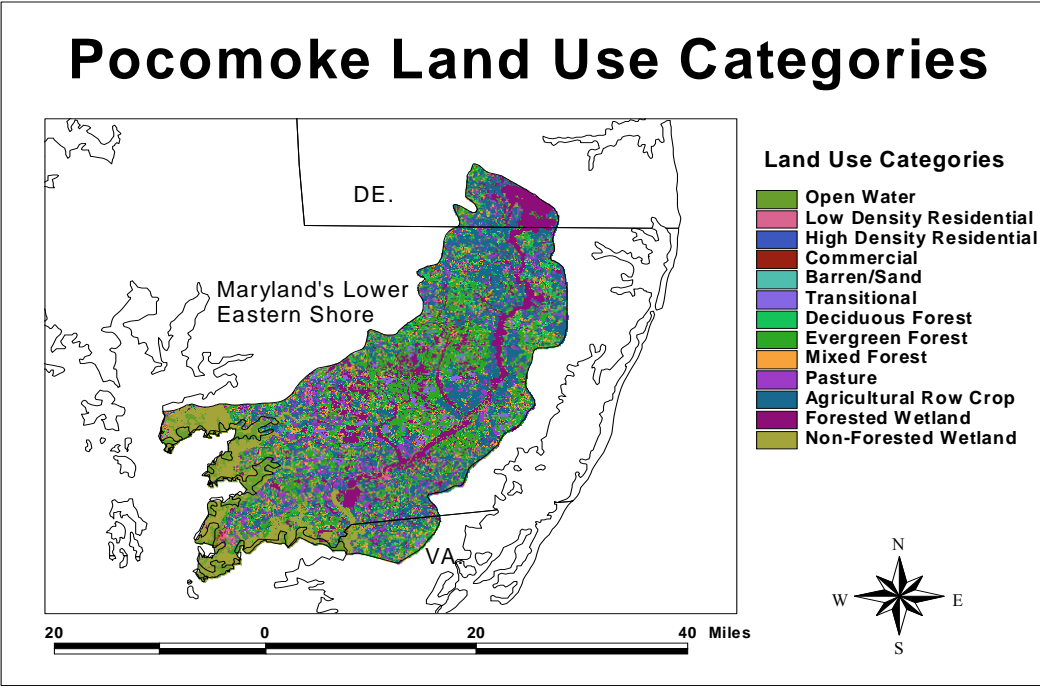
**Table 3.** NLCD LandUse codes<sup>17</sup> and equivalent SWAT codes used in the lookup table needed to convert NLCD data into usable SWAT references.

<b>NLCD Code:</b>	<b>NLCD Description:</b>	<b>SWAT Code:</b>	<b>SWAT Database:</b>	<b>SWAT Description:</b>
<i>Water:</i>				
11	Open Water	WATR	LandCover	Water
<i>Developed:</i>				
21	Low Intensity Residential	URLD	Urban	Residential-Low Density
22	High Intensity Residential	URHD	Urban	Residential-High Density
23	Commercial/Industrial /Transportation	UCOM	Urban	Commercial
<i>Barren:</i>				
31	Bare Rock/Sand/Clay	SWRN	LandCover	Southwestern US (Arid) Range
32	Quarries/Strip Mines/Gravel Pits	UIDU	Urban	Industrial
33	Transitional	SWRN	LandCover	Southwestern US (Arid) Range
<i>Forested Upland:</i>				
41	Deciduous Forest	FRSD	LandCover	Forest-Deciduous
42	Evergreen Forest	FRSE	LandCover	Forest-Evergreen
43	Mixed Forest	FRST	LandCover	Forest-Mixed
<i>Shrubland:</i>				
51	Shrubland	RNGB	LandCover	Range-Brush
<i>Non-Natural Woody:</i>				
61	Orchards/Vineyards/Other	ORCD	LandCover	Orchard
<i>Herbaceous Upland Natural/Semi-natural Vegetation:</i>				
71	Grasslands/Herbaceous	RNGE	LandCover	Range-Grasses
<i>Herbaceous Planted/Cultivated:</i>				
81	Pasture	PAST	LandCover	Pasture
82	Row Crops	AGRR	LandCover	Agricultural Land-Row Crops
83	Small Grains	HAY	LandCover	Hay
84	Fallow	AGRR	LandCover	Agricultural Land-Row Crops
85	Urban/Recreational Grasses	RNGE	LandCover	Range-Grasses
<i>Wetlands:</i>				
91	Woody Wetlands	WETF	LandCover	Wetlands-Forested
92	Emergent Herbaceous Wetlands	WETN	LandCover	Wetlands-Non-Forested

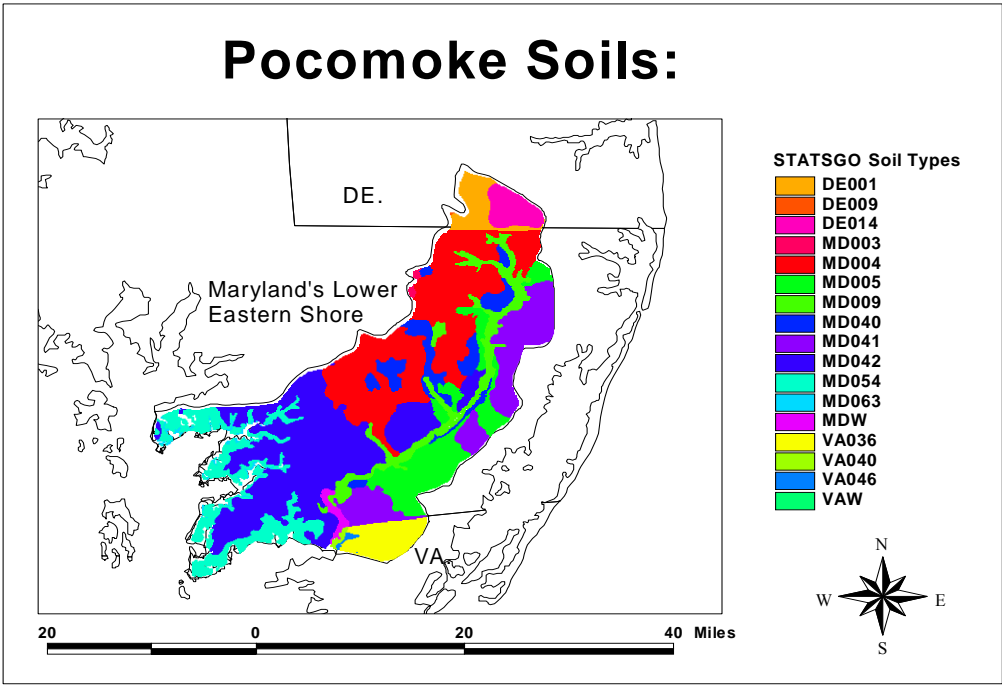
The table lists the NLCD code and description, as well as the nearest equivalent SWAT code and corresponding description, and the SWAT database in which the properties and variables values reside. Despite the numerous classification categories

available, a perfect match between the NLCD categories and the available SWAT classifications is not always found, and therefore the closest category available within the SWAT dataset is selected for each of the 21 categories included in the NLCD dataset. For this reason NLCD classifications of bare rock/sand/clay are reclassified using the nearest equivalent SWAT classification Southern US (arid) range, although clearly this classification does not ostensibly apply to locations within Maryland's eastern shore, although the physical description of the landuse category 'bare rock/sand/clay' is most closely identified in with the SWAT landuse classification for the 'Southern US (arid) range.' A fuller description of the land use and soil data and classifications used by SWAT in this project is contained in Appendices B and C, respectively.

Once the reclassification and overlay process is complete, a *Landuse and Soil Distribution* report is generated. The report provides information on the distribution of the land use and soil classes within the watershed and subwatersheds. Figure 15 and Figure 16 illustrate the diversity and spread of land use and soils data, respectively, as used in this study. The NLCD landuse map shows relatively intense diversity throughout the landscape, while the STATSGO soils maps utilizes a comparatively more homogenous and broad classification scheme. The soil type classifications used in Figure 16 refer to the STATSGO classification code for each soil type, for more descriptive information on each individual soil type refer to Appendix D.



**Figure 15.** Land cover categories presenting diversity of land use throughout the area of interest.



**Figure 16.** STATSGO soils classification for Pocomoke soils.

Following the determination of the landuse and soil classes, the HRU distribution procedure is used to define the location and coverage of HRUs within each subwatershed. During the process the user has the option of defining the resolution of the classification scheme by assigning a single HRU to each subwatershed defined by the dominant land use-soil combination characteristics, or by assigning multiple HRUs to each subwatershed with the possibility of eliminating landuse and soil classes that only comprises a relatively small or insignificant portion of the total subwatershed area. Limiting the resolution of the HRU definition process may be done in order to increase the efficiency of the SWAT calculations where the simulation covers a large area, however, during the process some of the detail associated with the landuse and soil maps imported is lost.

In the case of this project multiple HRUs are assigned to each subwatersheds, in order to maintain a relatively high-resolution detail. The percent of land use classes and soil classes of the total subwatershed area is summarized in the simulation summary included in Table 4. The HRU delineation process redefines the parameters described in the *LandUse and Soil Distribution* reports and generates a new report referred to as the *LandUse and Soil Distribution (after threshold application)*.

#### *SWAT Model Input and Execution:*

The next step in the development of the input files for SWAT model is the incorporation of weather data needed to run the simulation. For all simulations, weather data is generated based on built-in US weather databases. This weather data is obtained

from the National Climatic Data Center (NCDC)<sup>18</sup> (NOAA, 2004), which contains US weather datasets for over 1000 weather stations throughout the country. Generally, daily climatic data for the years 1971 to 2000 can be downloaded from this site for 52 sites throughout Maryland, a number of which are contained within the eastern shore and the specific area of interest.

The SWAT model allows the user to select these US weather databases, as done in this project, or to supply a custom *User Weather Station* database for a specific site of interest. SWAT loads appropriate weather gage stations and assigns to each subwatershed a specific gage station contained within the domain of the subbasin or within close proximity to it if a gage station is not located within the boundaries of the subbasin. The *Weather Data Definition* dialog box allows for the selection of this US data resource, and also allows the user to specify if data for rainfall, solar radiation, temperature, wind speed, and relative humidity is to be simulated or read from a real time or user supplied data source. For all cases weather data is simulated based on historical information. This information is contained within the simulation run details listed in Table 4.

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<sup>18</sup> Available online: <http://www.ncdc.noaa.gov/oa/ncdc.html>

**Table 4.** Summary of simulation run details including parameter values for Pocomoke watershed simulation, with and without irrigation.

<b>Model Parameter:</b>	<b>Source, Value or Method:</b>
<b><i>Watershed Delineation:</i></b>	
Elevation Map	National Elevation Database (NED)
Stream Delineation Map	National Hydrography Dataset (NHD)
Threshold Area	900 ha
<b><i>LandUse and Soils Classification:</i></b>	
Land Use File Source	NLCD
Soil Data Source	STATSGO
<b><i>HRU Definition:</i></b>	
Land Use Classes Eliminated	< 0%
Soil Types Eliminated	< 3%
<b><i>Weather Data Delineation:</i></b>	
Data Source	US Database (UCDC)
Weather Generation	All Values Simulated
<b><i>SWAT Simulation Procedures:</i></b>	
Period of Simulation	January 1, 2000 – January 1, 2020
Rainfall/Runoff/Routing	Normal Skewed
Potential ET Method	Penman-Monteith
Crack Flow	Not Active
Channel Water Routing	Variable Storage
Channel Degradation	Not Active
Stream Water Quality Processes	Active
Lake Water Quality Processes	Active
Printout Frequency	Both Monthly and Yearly

The loading and coding of weather data is the final step of the data input phase. At this stage in the model development, if loaded correctly, all essential information is contained within one of three sources: the GIS spatial data and associated attribute tables; the standardized internal database files provided with SWAT or the user developed database files for special needs; and the weather files linked to each subbasin.

The next step is the translation of this information into the required SWAT input files described in the introductory material of this report. The generation of the 12 SWAT input files is an automated process within the ArcView-SWAT program, but can be manually executed for specified files in cases where modifications are made to



specific input data sources or where more control is required. The process automatically pulls in required information from each of the three sources listed above and assimilates the information into the required SWAT ASCII input file format. Once created, the generated default values included in these input files can be modified or edited following file creation. This may be necessary in fine tuning and calibrating the input files to better reflect apparent conditions that may not be accurately represented in the default databases.

Once input files are compiled the SWAT program is executed. During this final step the user is able to select the method of calculation for runoff and potential evapotranspiration, the duration and time interval of the simulation, the printout frequency and a few calculation procedures with regards to crack flow, water routing and water quality. The options selected for all simulations conducted in this study are listed in the simulation details summary included in Table 4.

The final simulation screen also allows the user to check input parameters, in order to ensure that all inputs are within a specified range, and make necessary adjustments to specific values or redefine the acceptable range as needed. This process was conducted repeatedly prior to final execution as the range of input parameters varied from expected values.

Therefore, for the execution of this model, it was necessary to redefine some of the acceptable variable ranges associated with various SWAT databases, in order to accommodate the specific variable values associated with the Maryland data used. A list of the default ranges altered during the execution of SWAT, and the databases that they affect is included in Table 5. Note that this does not alter any of the values used, but

rather redefines the acceptable range of allowable values used by SWAT during the calculation and modeling phase, which better reflects the conditions associated with Maryland's eastern shore.

**Table 5.** Range of modifications made to default SWAT input database files.

Parameter:	Original Range:	Modified Range:	Variable Definition:
<b>File: solrng.dbf</b>			
SOL_CBN	0.05-10.00	0.04-10.00	Organic Carbon Content [%]
SOL_BD	1.10-2.50	0.30-2.50	Moist bulk density
<b>File: hrurng.dbf</b>			
SLSUBBSN	10.0-150.0	0.05-150.0	Average slope length [m]
SLOPE	0.000-0.600	0.000-1.050	Average slope steepness [m/m]
<b>File: mgtrng.dbf</b>			
CN2	35-98	25-98	SCS runoff curve number for moisture conditions II
<b>File: croprng.dbf</b>			
RDMX	0.00-3.00	0.00-3.50	Max root depth [m]
BIO_E	10.0-90.0	0.0-90.0	Biomass/energy ratio
HVSTI	0.01-1.25	0.00-2.00	Harvest index
BLAI	0.5-10.0	0.0-10.0	Max leaf area index
DLAI	0.15-1.00	0.0-1.00	Fraction of growing season when leaf area starts declining
CHTMX	0.1-20.0	0.0-20.0	Max canopy height [m]
T_OPT	11-38	0-38	Optimal temp for plant growth [°C]
CNYLD	0.0015-0.075	0.000-0.075	Fraction of nitrogen in seed
CPYLD	0.0001-0.0150	0.0000-0.0150	Fraction of phosphorus in seed
BN1	0.004-0.070	0.000-0.070	Fraction of N in plant at emergence
BN2	0.002-0.050	0.000-0.050	Fraction of N in plant at 0.5 maturity
BN3	0.001-0.270	0.000-0.270	Fraction of N in plant at maturity
BP1	0.0005-0.0100	0.0000-0.0110	Fraction of P in plant at emergence
BP2	0.0002-0.0070	0.0000-0.0070	Fraction of P in plant at 0.5 maturity
BP3	0.0003-0.0035	0.0000-0.0035	Fraction of P in plant at maturity
USLE_C	0.001-0.500	0.000-0.500	Min value of USLE C factor applicable to the land cover/plant
VPDFR	1.0-6.0	0.0-6.0	Vapor pressure deficit corresponding to the fraction maximum stomatal conductance defined by FRGMAX
CO2HI	300-1000	0-1000	Elevated CO <sub>2</sub> atmospheric concentration [ppm]
BIOEHI	5-100	0-100	Biomass-energy ratio corresponding to the 2 <sup>nd</sup> point on the radiation use efficiency curve
RSDCO_PL	0.010-0.099	0.000-0.099	Plant residue decomposition coefficient

The result is a series of output data files, described in the introductory material of this report, that serve as the basis for the execution of the irrigation economic application.

The SWAT output database files created at the end of the simulation are used as a

resource containing all hydrological values generated on a daily, monthly or annual time step. For the purposes of determining irrigation schedules these generated report files are created at a monthly time step. Assessment of the environmental impact of irrigation with regards to nutrient loading is conducted on a yearly time step.

*SWAT Model Calibration:*

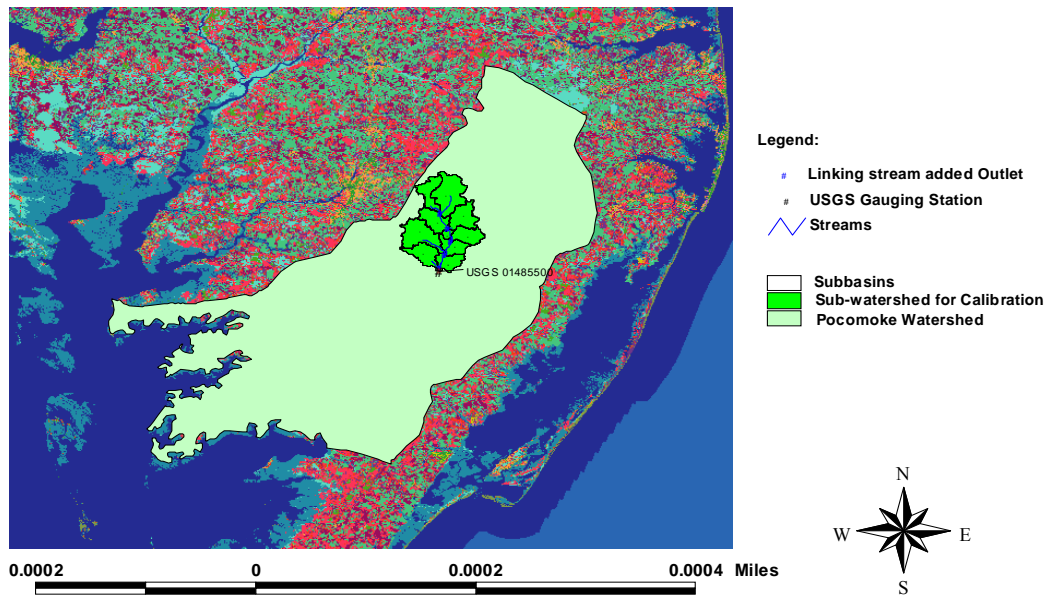
The validity of the irrigation economic component of this study depends heavily upon the output data provided by the SWAT simulation. Considerable reference has already been made to the nature of the input grids and data supplied to the SWAT model as of which have been obtained from reputable governmental sources. However, it is also necessary to validate the model by comparing modeled output parameters to actual measured data in order to determine if the model is reasonably accurate. This sort of calibration is achieved by adjusting certain model parameters in order that model output better conforms to available onsite data.

The hydrological component of the SWAT model is compared with stream flow data obtained from a USGS gauging station (station number 01485500), located along the Nassawango Creek near Snow Hill, Maryland in Worcester County (latitude: 38°13'44.1", longitude: 75°28'17.2")<sup>19</sup>. The subwatershed supplying the Nassawango Creek at the specified USGS gauging station is identified in Figure 17, and is used to calibrate the Pocomoke watershed simulations, by comparing the measured stream flow values obtained from the USGS database with model calculated stream flow values at the same point under various calibration scenarios.

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<sup>19</sup> USGS Stream flow gauging station data is available on line at: [http:// waterdata.usgs.gov/nwis/rt](http://waterdata.usgs.gov/nwis/rt).

# SWAT Calibration



**Figure 17.** Location of USGS Gauging Station # 0148550 used in the calibration of the SWAT model.

Model calibration was conducted for a 6-year period extending from January 1, 1990 to December 31, 1995. This time frame coincides with the dated USGS national land cover maps, which are based on satellite images obtained in 1992. The SWAT calibration simulation uses daily maximum/minimum temperature values, precipitation, and solar radiation values for the simulation time frame (1990-1995) obtained from a weather station located in Salisbury, Maryland in Wicomico County<sup>20</sup>, relatively near the watershed drainage area upstream of the USGS gauging station used for calibration for this study.

<sup>20</sup> Weather station data is provided by NOAA on line at: <http://www.ncdc.noaa.gov>

Without changes to model variables, the calculated average annual total water yield in the stream channel located at USGS gauging station is estimated to be 455 mm; while the average water yield measured at this point is 378 mm, a 16.9% difference. Modest adjustments to various model parameters including, the SCS curve number (CN2), the available soil water content (SOL\_AWC), and the soil evapotranspiration compensation factor (ESCO), were made during a calibration scenario in order to better reflect measured data. The SWAT simulation using calibrated variable adjustments reduced this difference to 10.6%, which is considered to be within an acceptable range. Subsequent model simulations used these modifications in order to better estimate the hydrology of the region.

The most direct impact in reducing the overall calculated water yield in the channel at the point of the USGS gauging station, is achieved by adjustment of the SCS curve number. Higher curve numbers reflect less permeable conditions, with a curve number of 100 indicating completely impervious conditions, while lower curve numbers indicate more permeable conditions and vary with landuse and land cover conditions.

In the case of the model calibration scenario, input curve numbers were universally decreased by 8 points, thereby reflecting more permeable conditions. As stated above prior to calibration, SWAT stream flow calculations were higher than USGS measured data, therefore, a lower curve number increases infiltration thereby reducing the volume of water entering the channel.

Further modifications include increasing the available soil water content by 5% resulting in a slightly greater water holding capacity of the soil profile. The resultant effect is an increase in the water storage capacity of the soil making more water available

for plant use and to meet the evapotranspiration demand. Water not used to meet the evapotranspiration demand would otherwise further contribute to the stream flow. Likewise, the soil evaporation compensation factor is decreased by 0.5 in the calibration scenario. This variable affects the depth distribution of water used to meet the evaporative demand accounting for the effect of capillary action, cracks and crusting, allowing for more of the demand to be supplied by lower soil levels, thereby having a very modest effect on the water volume contributing to stream flow. Soil cracks and crusting is likely to be less prevalent in Coastal Plain sandy soils, and therefore the reduction of the soil evaporation compensation factor is a reasonable alteration.

Other variables found to affect the total water yield calculation include: the groundwater coefficient regulating the upward movement of water (GW\_REVAP), the minimum threshold depth variable (REVAPMN) used in determining the upward movement of water from shallow water sources, and the threshold depth of water in the shallow aquifer (GWQMN) required for baseflow to occur. Each of these variables affects when and to what degree subsurface flow occurs, and therefore indirectly govern the contribution of subsurface flow to the total stream flow of the watershed of interest. However, it has been found that only very substantial changes in these values effect a noticeable change in the water yield calculations, and therefore adjustments to these values have been left out the calibration scenario.

Table 6 compares the SWAT calculated water yield before and after calibration modifications with the USGS measured stream flow data for the same point within the Pocomoke watershed for each year of the calibration simulation. Note that stream flow is reported by the USGS as average daily flow rates in cubic feet per second, and therefore

is converted into a total annual water yield, calculated for each year using the total area of the upstream watershed, approximately 11,600 hectares which reflects the upstream drainage area contributing to the total stream flow measured at the point of the USGS gauging station.

**Table 6.** Comparison of SWAT calculated and USGS measured stream flow before and after calibration for each year of the simulation.

Year:	Salisbury	SWAT Data		USGS Data
	Precipitation Data (mm)	Default Water Yield (mm)	Calibrated Water Yield (mm)	Stream Flow Water Yield (mm) <sup>21</sup>
1990	986.6	341.4	322.8	345.47
1991	1086.3	414.9	387.8	303.57
1992	1255.4	522.6	495.9	404.74
1993	1143.7	475.2	437.3	492.56
1994	1366.9	639.7	576.4	532.31
1995	902.5	355.2	317.4	187.46
Average:	1123.6	454.8	422.0	377.7

### **Watershed Delineation and Description:**

The paragraphs that follow describe the Pocomoke watershed as modeled in SWAT. At each stage in the development of the model, and following the execution of individual simulations, summary reports and output files are generated. The information contained within these summary reports describes the salient features of the watershed and the pertinent details related to the objectives of this study. The information presented below is distilled from these reports and reflects model conditions as defined by the quality of the input data, which may vary from actual field conditions. Physical data

<sup>21</sup> Calculated from daily average stream flow data.



concerning topography, land use, soil types and area discretization is held constant for all SWAT simulations and is described below.

*Topographical Report:*

The first step in the model development involves defining the overall area of interest, and the individual subbasins. Pocomoke watershed defined for all model simulations extends over an area of 117,000 ha and is subdivided into 79 subbasins varying in their respective coverage area and the associated elevation range contained within each subbasin area. As a whole the Pocomoke watershed has an average elevation of 9.6 m with a standard deviation of  $\pm 4.0$  m, ranging from  $-1.1$  meters to 24.6 meters. This summary information is obtained from the ‘*Topographical Report*’ generated following the watershed delineation process and excludes areas designated by SWAT as ‘sinks,’ which refer to mostly low lying wetland areas at or below sea level where water does not properly flow out of the watershed according to SWAT drainage calculations.

*Sub-Basins Description Based on the Land Use and Soils Report:*

Each subbasin is divided into hydraulic response units comprised of a unique land use and soil type combination as described previously in this section. Based on the NLCD grid SWAT classified the Pocomoke watershed into 12 land use classifications with the greatest proportion of that land, nearly 27.9 % or 30,580 ha, classified as agricultural land-row crops. A breakdown of the diversity and percentage of land use types is included in Appendix C of this report, as well as the percentage of agricultural row-crop land associated with each subbasin.

Considering soil classification data alone, the Pocomoke watershed includes 16 soil types classified according to the Natural Resources Conservation Service (NRCS) STATSGO classification scheme. Table 7 lists each soil type contained within the Pocomoke watershed and ranks them in order of relative coverage. The greatest percentage of the land is covered by the soil classification MD041, part of the ‘Pocomoke’ soil series characterized as sandy loam with a weak fine granular structure, having high organic content and is strongly acidic (NRCS, 2004a)<sup>22</sup>. These soil qualities are the dominant soil characteristics found throughout much of the region. This soil classification is used with each model simulation described in the paragraphs that follow.

**Table 7.** Soils categories and percent coverage of each soil type for the Pocomoke watershed as a whole.

<b>Soil Classification:</b>	<b>Area [ha]:</b>	<b>Area [acres]:</b>	<b>Percentage of Watershed [%]:</b>
MD041	40662.7	100479.6	34.80
MD005	19897.1	49166.8	17.03
MD063	14779.1	36519.9	12.65
MD040	12737.5	31474.9	10.90
MD009	8690.9	21475.5	7.44
MD004	8443.4	20864.0	7.23
DE009	5279.8	13046.6	4.52
VA037	2882.9	7123.8	2.47
DE014	2752.4	6801.3	2.36
MD042	308.9	763.3	0.26
MD003	213.9	528.6	0.18
VA040	67.8	167.5	0.06
DE001	54.2	133.9	0.05
MD054	31.4	77.6	0.03
VA046	36.6	90.5	0.03
VA036	7.4	18.2	0.01

<sup>22</sup> For complete soil description see: <http://ortho.ftw.nrcs.usda.gov/osd/dat/P/POCOMOKE.html>

A full description of each soil type, included in Table 7, can be obtained from the NRCS website<sup>23</sup>, however, summary information including the hydrologic group to which each soil type belongs, the relative percentage of clay, silt and sand for each soil layer, and the basic physical properties such as the soil hydraulic conductivity and the available soil-water content, can be found in the summary tables included in Appendix D. This summary information describes the salient characteristics of each soil type and the top four soil layers where applicable.

### **Customized Program Integration and Model Development:**

The primary thrust of this project revolves around the development of an irrigation program, to determine if supplemental irrigation is profitable, and to determine the overall optimal agricultural water demand for a given region. This irrigation-economic component of the model is based upon the foundation of user-supplied data and the SWAT output files that are created during the SWAT model simulation described above. The discussion below describes the factors incorporated into the supplemental irrigation program developed within the Microsoft Visual Basic 6.0 ® environment, followed by a description of the steps involved in executing the program. The program code is included in Appendix F of this document.

#### *Irrigation-Economic Modeling Components:*

The first step in the development of the *IrrigEcon* model is to determine which agricultural crop fields would profit from the installation of supplemental irrigation systems. In the model this is done by comparing profits from crop yields with and

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<sup>23</sup> Descriptive information for each soil type can be obtained from the NRCS soils website: <http://soils.usda.gov/>

without irrigation, and matching the difference against the projected combined irrigation installation, maintenance and operation costs. This requires the use of estimated irrigation costs, incorporating the capital depreciation and maintenance costs presented in Table 45 of Appendix E, for each irrigation system under consideration. Yields with irrigation are estimated based on the application of the optimal volume of irrigation water considering economic variables associated with its application, as will be discussed further in this section.

The variable cost associated with the operation of the irrigation system reflects the water supply cost, in terms of the electrical pumping cost, if water is obtained onsite, or the market cost, if water is obtained from municipal sources. This associated cost is considered to be directly proportional to the water quantity consumed. In the case of this study, it is assumed that all water for irrigation purposes is obtained onsite from a local borehole or reservoir.

In order for irrigation to be profitable, the costs associated with irrigation must be surpassed by the projected benefit due to increased yields, which is simply the value to the farmer of the additional crop, above and beyond expected yields without irrigation. The additional yield due to irrigation is equated to increased revenue to the farmer and is used to determine the overall net benefit of irrigation installations.

In this evaluation, the prices received by the farmer for agricultural goods are assumed to be constant and do not vary with supply. Idealistically, this may be an invalid assumption with market prices increasing with declining supply levels generally associated with periods of drought, making any increase in crop yields, as a result of irrigation, more profitable especially during drought years. However, in today's global

economy, where it is possible to ship agricultural goods over great distances, from areas of high productivity to regions of insufficient production, the complexity of market pricing can be difficult to predict and is beyond the scope of this current study. Instead this simplistic economic-irrigation model considers a constant market price for all crops, under both drought and non-drought conditions.

The market prices used in the present model are presented in Table 8. These values represent the average seasonal price received by Maryland farmers in 2003 (MASS, 2004), as reported by the Maryland Agricultural Statistics Service (MASS). This table also includes the percentage of total agricultural cropland in Maryland dedicated to the production of each crop commodity in 2003 (the latest statistical summary information at the time this study was carried out). For the purposes of this model it will be assumed that these relative proportions remain constant over multiple years even if a crop rotation is used for individual fields.

**Table 8.** Cropland and the average seasonal crop prices received by Maryland farmers in 2003 (MASS, 2004).<sup>24</sup>

<b>Crop Type:</b>	<b>Acres Harvested:</b>	<b>Percentage of Total Crop Land [%]:</b>	<b>Reported Price Received by Farmer:</b>	<b>Converted Price Received by Farmer [\$/metric ton]:</b>
Corn	505000	33.14	2.85 \$/bushel	112.20
Soybean	470000	30.84	7.25 \$/bushel	266.40
Hay	220000	14.44	150.00 \$/ton	150.00
Wheat	180000	11.81	3.15 \$/bushel	115.75
Alfalfa	45000	2.95	143.00 \$/ton	143.00
Barley	41000	2.69	1.80 \$/bushel	82.70
Sorghum	5000	0.33	2.55 \$/bushel	100.40
Potato	4700	0.31	8.8 \$/100 pounds	194.50
Vegetables <sup>25</sup>	52100	3.42	Various	Various

*Irrigation-Economic Model Execution:*

The Irrigation Economic Decision Support tool (*IrrigEcon*), consists of four sections or steps, which must be executed sequentially if the program is to operate properly, and are described below. The first two steps involve the import and modification of required data, while the final two-steps involve model calculations and output of specific recommendations.

Step 1: Input File Selection:

The program accepts as required input files three ASCII text files containing all required information including: installation/operation costs and efficiencies of the irrigation systems under consideration; the crop economic data, including prices received and production costs; as well as the output data from the SWAT simulations.

<sup>24</sup> Available online WWW: <http://www.nass.usda.gov/md/Ag%20in%20Maryland%202003.pdf>

<sup>25</sup> Includes vegetables and other crops: asparagus, beets, broccoli, cabbage, cantaloupes, cauliflower, carrots, cucumbers, eggplant, greens, green peas, hot peppers, kale, lettuce, lima beans, pumpkins, okra, snap beans, spinach, squash, strawberries, sweet corn, sweet peppers, sweet potatoes, tomatoes, turnips, and watermelon.

The program runs independently of SWAT requiring only the SWAT .sbs output file described in the introductory material of this report. The .sbs output file is generated by SWAT at the end of each simulation and provides values of key parameters associated with each HRU and recorded at specific time intervals (daily, monthly or annually) for the duration of the simulation. The .sbs filename varies with each the SWAT simulation, and therefore must be selected prior to the execution of the *IrrigEcon* program.

By default two text files have been included with the program containing default irrigation system and crop economic data, and include values for each variable as described above in Appendix D. However, the user may wish to use alternative values and therefore the option has been included to allow the user to select an alternative irrigation or crop input data file, which must be in the same format as the original text files.

#### Step 2: View/Modify Input Data.

The second section of the program allows the user to view and modify input data. This section of the program allows the user to view individual records included in each of the three input files, and modify the irrigation and crop economic data, saving any revised information. However, the imported SWAT .sbs output data can only be viewed, as this data is the result of simulation calculations. Therefore, as a precaution these values have been locked for editing in order to avoid unintentional mistakes.

However, the program allows for the modification of irrigation and crop economic data, as this information is variable depending on specific site or regional conditions and may vary significantly from year to year. As stated in the introductory

material of this report, crop production and revenue prices were gleaned from Maryland statistical data for 2003, while irrigation installations were based on estimates of Jim Fouks from Self Propelled Irrigation in December of 2004<sup>26</sup>.

The user may wish to use more conservative values in order to include a safety factor in the calculation of net benefit values, or may have available more pertinent irrigation installation/operation or water cost for his/her farm, which would be more appropriate than the rough estimates included in the default files. In this way the user may also include economic data from additional irrigation systems or crops that have not been included in the default files provided. Once the desired modifications have been made the user can either overwrite the default input text files or save the data to a new data text file.

### Step 3: Net Benefit Calculations.

By default, irrigation economic data has been included for three irrigation systems (Center Pivot, Traveling Gun and Drip Systems). However, each of these systems may not be appropriate for all crop types or circumstances. For instance drip irrigation may not be appropriate for small grains and other high-density field crops, while sprinkler irrigation may not be appropriate for crops sensitive to fungal disease such as melons and cantaloupe; therefore, the user may wish to evaluate the net benefit of only one type of irrigation system or alternatively compare all three systems. This section of program allows the user to select which systems to run during the net benefit analysis, if the user is not comparing all systems directly.

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<sup>26</sup> Personal communication (December 9, 2004) with Mr. Jim Fouks of Self Propelled Irrigation (410 673-7885), Preston MD.



#### Step 4: Generate Output Files and Make Recommendations.

The last and final stage of the program execution produces two outcomes. First, it generates output files that list all agricultural HRU's included in the SWAT .sbs file and identifies those fields that will benefit from the installation an irrigation system according to the input data provided, and directly compares the net benefit of each system in order to recommend a single system for each field (if a positive net benefit is determined).

Secondly, the program generates an output file that estimates the annual irrigation water demand for each HRU based on the optimal demand for the recommended irrigation system/crop combination. This analysis takes into account the cost of water in order to determine optimal water demand based on the highest economic net benefit attainable. The output files generated, summarize predicted optimal irrigation water demand on a subbasin and watershed scale (as defined in the SWAT simulation).

#### *Net Benefit Calculations:*

Theoretically, any positive net benefit can be considered a justification for irrigation installation, although a significant margin of error should be included before any substantial investment is seriously considered, mostly due to the uncertainty of the assumed costs and the variability in the expected life of the selected irrigation system. Equation 19 calculates the approximate net benefit of irrigation installations, for each year of the simulation, based on a simple summation of farm expenses and estimated revenue.

In the case of this study, three distinct irrigation systems are considered, each of which is associated with their own installation and operating costs, therefore, three

irrigation benefit projections must be calculated. This will constitute part of the decision support system that will aid farmers in determining which irrigation system is best suited for their particular needs and site conditions. Equation 19a calculates net benefit based on both the variable and fixed costs of production, while equation 19b simplifies this calculation by including a single value for the combined production costs, as described below. These equations are modified from the Mannocchi and Mecarelli (1984) equation, presented previously in this text as equation 18.

$$NB_I = (Y_t)(P_s - C_1) - (C_0 + C_{ID}) - Vol_I(C_w) \quad (19a)$$

Where,  $Y_m \geq Y_t \geq YLD$

This is simplified for the purposes of this study as the following:

$$NB_I = (Y_t) \cdot P_s - (C_p + C_{ID}) - Vol_I(C_w) \quad (19b)$$

Where,  $Y_m \geq Y_t \geq YLD$

Where,  $NB_I$  is the net benefit with irrigation [\$/ha],  $Y_m$  is the maximum yield assuming full growth [tons/ha],  $Y_t$  is the target yield with supplemental irrigation [tons/ha],  $YLD$  is the yield obtained without supplemental irrigation [tons/ha],  $P_s$  is the sale price of yield [\$/ton],  $C_0$  is the fixed cost of production per unit area [\$/ha],  $C_1$  is the cost varying with yield [\$/ton],  $C_w$  is the cost of water per unit volume [\$/m<sup>3</sup>],  $C_p$  is the agricultural cost of production [\$/ha],  $C_{ID}$  is the irrigation installation net depreciation for

the time step [\$/ha], and  $Vol_t$  is the irrigation volume applied per unit area over the time step [ $m^3/ha$ ].

The target yield ( $Y_t$ ) included in the equation above represents a value greater than or equal to the actual yield without irrigation ( $YLD$ ), but less than the maximum potential yield ( $Y_m$ ) for a particular crop species. Only in the case where supplemental irrigation is not prescribed will the target yield equal the actual yield. Supplemental irrigation is prescribed in the case where the market value of the yield difference between the attainable target yield with irrigation and the actual yield without irrigation is equal to or greater than the operational cost of the irrigation equipment, including the annual depreciation and maintenance costs of the irrigation equipment and the cost of water per unit volume.

The combined averaged agricultural production cost is estimated to be 485 \$/ha·year based on the average farm size and the average production cost for Maryland farmers in 2003 as reported by MASS (MASS, 2004). This value is calculated by dividing the average production cost of all agricultural farms in Maryland with the average size of Maryland farms. This value includes both variable and fixed costs and does not distinguish between the various crop types being produced or the size of the farm, but rather gives only the average production cost for all farms in Maryland.

Ideally, the production expense should consist of both an average fixed cost of production per hectare based on farm size, as well as a variable cost varying with the yield and crop type being produced, as presented in equation 19a. However, in the absence of this detailed information the average production cost for Maryland farmers is based on the average combined variable and fixed cost per hectare derived from

information provided by MASS. This single value for production cost ( $C_p$ ) is used in the simplified equation (19b), however, this procedure can be expanded if more detailed economic information is obtained.

The purpose of equations 19a and 19b is to relate the net benefit of irrigation to an irrigation application quantity. This is achieved by linking the applied irrigation volume to evapotranspiration rates (given in mm of water) with and without irrigation. The irrigation volume used in equations 19a and 19b can be expressed as the depth of irrigation applied over the entire HRU, as shown in equation 20.

$$Vol_I = \frac{I_D \cdot A}{EFI \cdot 10} \quad (20)$$

Where,  $Vol_I$  is the irrigation volume applied per unit area over a given time step [ $m^3/ha$ ],  $I_D$  is the effective minimum irrigation depth applied [mm],  $A$  is the unit area [ha or  $10,000 m^2$ ], and  $EFI$  is the total irrigation efficiency [dimensionless].

The equation above uses an irrigation efficiency value ( $EFI$ ), which varies with the type of irrigation system being used. No irrigation system will distribute the exact same quantity of water to each unit area of the field being irrigated; therefore, an efficiency variable is introduced to account for this inequitable distribution.

Under general conditions, in order that all segments of a field receive a minimum amount of water, irrigation must be applied in excess, such that, the area receiving the lowest water application receives a predetermined minimum quantity. As a result other sections of an irrigated field may receive an excess supply of water, which is, for the most part, underutilized or wasted. Irrigation systems resulting in the least waste have

the highest irrigation efficiency, which can be a function of the irrigation emitter mechanism being used, the design and configuration of the irrigation system, the supply operating pressure, and the landscape and terrain of the area being irrigated.

The irrigation efficiency values used in this model are presented in Table 45 of Appendix E, for each irrigation system considered. This table also contains installation costs, equipment depreciation and maintenance costs associated with each irrigation system. These values are required for the development and execution of the economic component of this model. In general, systems with higher irrigation efficiencies are associated with higher equipment and/or installation costs, but use less water, thereby reducing the overall cost of water. This model, as part of a decision support system, will be used to determine which irrigation system, given its associated cost and efficiency, is most suited for each agricultural field.

The unknown variable in equation 20, for determining the applied irrigation volume ( $Vol_I$ ), is the irrigation depth ( $I_D$ ) required to satisfy plant needs. This value must be related to the target plant evapotranspiration requirements. As stated in the introductory material of this document, evapotranspiration rates are related directly to crop yield, where a maximum yield is achieved at the maximum potential evapotranspiration rate. Therefore, in order to determine the required irrigation depth ( $I_D$ ) the target evapotranspiration rate ( $ET_t$ ) associated with the target yield ( $Y_t$ ), used in equation 19, must be determined.

SWAT calculates actual and potential evapotranspiration and sets them as output variables summed over each recorded output interval. In this case the actual evapotranspiration value calculated by SWAT is the evapotranspiration value associated

with no irrigation. Therefore, the applied irrigation depth must account for the difference between the target and actual evapotranspiration values. Under irrigated conditions the target evapotranspiration rate will range between the actual evapotranspiration, without irrigation, to the potential evapotranspiration under well-watered conditions, and will vary with the target yield. Only in the case where there is no cost associated with water application will the target evapotranspiration be equivalent to the potential evapotranspiration. In such a case the optimal economic yield is equivalent to the maximum yield, which is achieved when the evapotranspiration rate is equivalent to potential evapotranspiration.

In the case where there is a cost associated with water application, the optimal water application rate is achieved when there is a negative or zero net benefit association with an incremental increase in the application volume, meaning that any additional water applied will result in a negative economic return. The resulting water application will cost the farmer more money to apply than he/she can expect in return due to increased yields (if any marginal yield increase is obtained). In such a case, the target yield is below the maximum yield, just as the associated target evapotranspiration rate is below the maximum potential evapotranspiration. However, in both cases the ratio of the actual yield to the target yield and the actual evapotranspiration to the target evapotranspiration is not known.

Projected yield values without irrigation are obtained directly from the SWAT output .sbs file, however, the target and potential yield values ( $Y_t$  and  $Y_m$ ) are calculated values using equation 7 presented previously in this text, which associates actual and potential evapotranspiration rates with actual and potential crop yields. This is a linear

equation relating the ratio of actual to potential evapotranspiration to the ratio of actual to maximum yield. This linear relationship is modified in this analysis such that it relates the ratio of actual to target evapotranspiration (without and with irrigation) to the ratio of actual to target yield (without and with irrigation).

By solving for the target or maximum yield using the modified equation 7 described above, and substituting for this value in equation 19b results a new equation from which the optimal irrigation quantity, applied over the course of the time step, is determined. This new equation, in terms of the optimal irrigation demand volume, is presented as equation 21. The volume of water associated with the maximum net benefit for irrigation is determined through a series of iterations, systematically increasing the irrigation volume applied, until a maximum net benefit is achieved. The equation below yields a positive net benefit value if and only if irrigation is profitable given the costs associated with water use and agricultural production. Therefore, once determined, this calculated value, for the net benefit of irrigation, is used to prescribe irrigation installation if the calculated net benefit is greater than the net benefit of production without irrigation.

$$NB_I = \left( \frac{YLD}{1 - k_y \left[ 1 - \frac{ET_a}{ET_t} \right]} \right) \cdot P_s - [(C_p + C_{ID})] - \left[ \frac{I_D \cdot A}{EFI \cdot 10} \cdot C_w \right] \quad (21)$$

Where,  $NB_I$  is the net benefit with irrigation [\$/ha],  $YLD$  is the harvested yield without supplemental irrigation [tons/ha],  $P_s$  is the sale price of yield [\$/ton],  $C_w$  is the

cost of water per unit volume [ $\$/\text{m}^3$ ],  $C_p$  is the agricultural cost of production [ $\$/\text{ha}$ ] ( $\$500/\text{ha}\cdot\#\text{of time steps}$ ),  $C_{ID}$  is the irrigation installation net depreciation and maintenance for the time step [ $\$/\text{ha}$ ],  $ET_a$  is the actual evapotranspiration [mm],  $ET_t$  is the target evapotranspiration [mm],  $k_y$  is the a crop yield response factor [dimensionless],  $I_D$  is the effective minimum irrigation depth applied [mm],  $A$  is the unit area [ $10,000 \text{ m}^2 / \text{ha}$ ], and  $EFI$  is the total irrigation efficiency [dimensionless].

The optimal ratio of actual to target evapotranspiration, used in the equation above, represents an unknown quantity varying with the cost of water and the return on increased yields. A specific actual to target evapotranspiration ratio can be related to the average point at which irrigation is initiated, and then compared to other cropping systems as a means of determining the relative importance of irrigation between crops. Crops for which irrigation is initiated at a relatively high actual to potential evapotranspiration ratio, based on the calculated net benefit, have greater relative value than a crop where irrigation is initiated at a significantly lower evapotranspiration ratio.

The next step is to relate the target evapotranspiration to the applied irrigation volume, which represents two unknowns in the equation above. The target evapotranspiration is simply the water volume that must be supplied to the crop in order to achieve the target yield. This is approximated as the sum of water entering and exiting the root zone through natural processes and from applied irrigation.

This relationship is presented as equation 22a, which presents the target evapotranspiration in terms of the prescribed effective irrigation depth and known values determined by SWAT. This equation is simplified in equation 22b by using the actual evapotranspiration to represent the water volume used by the crop under non-irrigated



conditions. In this case, the effective irrigation depth ( $I_D$ ) represents the water volume required to make up the difference between the actual and target evapotranspiration volumes, without consideration of applicable inefficiencies associated with irrigation scheduling practices and water application/distribution for various irrigation systems. Equation 22b is then substituted into equation 21 in order to arrive at a single equation with one unknown, (i.e. the optimal volume of applied irrigation water). Note that infiltration in the equation below is estimated as the difference between precipitation and surface runoff, due to the fact that SWAT outputs precipitation and surface runoff values for each time step, but does not list a specific value for infiltration.

$$ET_t = I_D + (PRECIP - SQ) - PERC - LQ + RVAP \quad (22a)$$

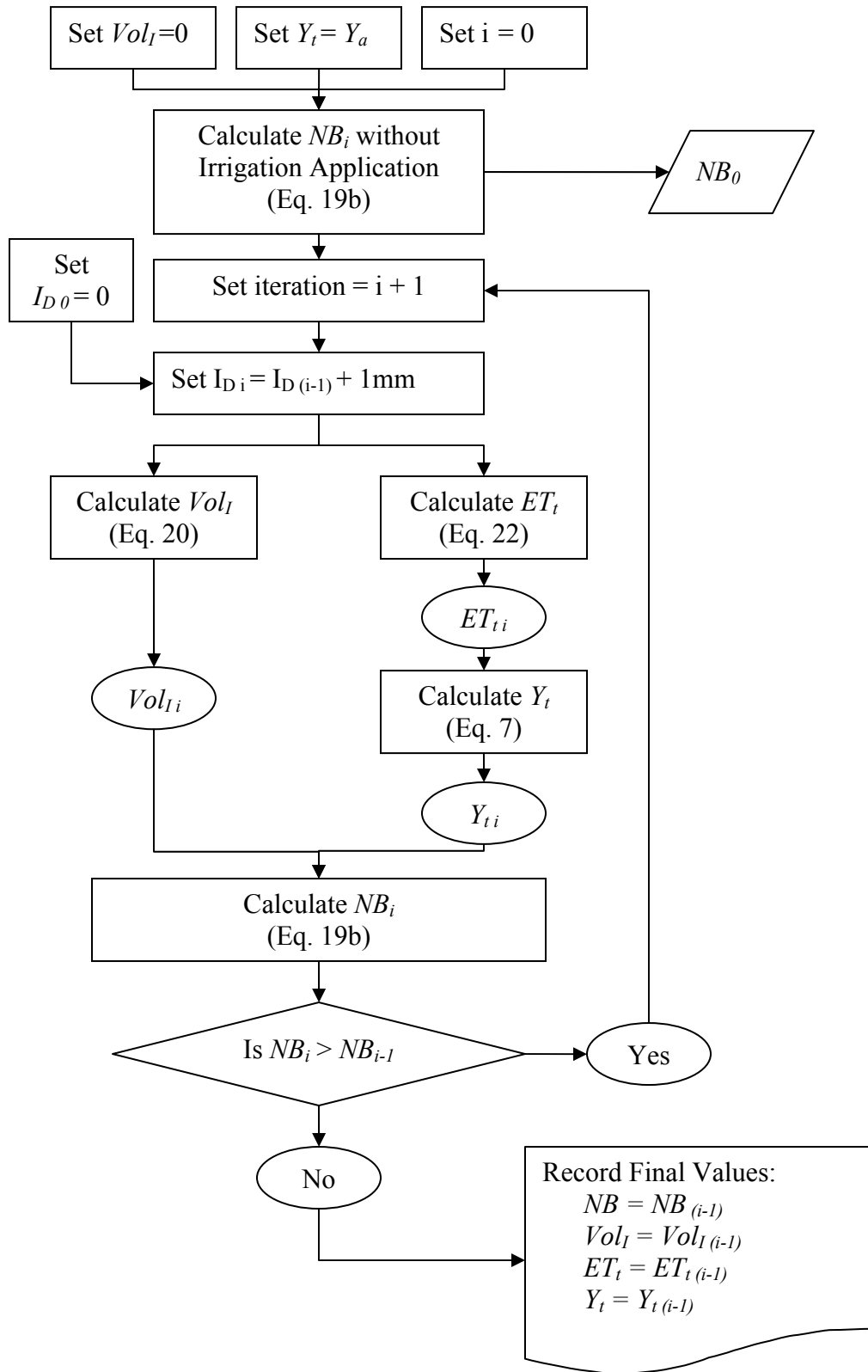
$$ET_t = I_D + ET_a \quad (22b)$$

Where,  $I_D$  is the effective minimum irrigation depth applied [mm],  $ET_t$  is the target evapotranspiration [mm],  $ET_a$  is the actual evapotranspiration [mm],  $PRECIP$  is the amount of precipitation falling during time step [mm],  $SQ$  is the surface runoff during time step [mm],  $PERC$  is the percolation past the root zone during time step [mm],  $LQ$  is the lateral flow during time step [mm], and  $RVAP$  is the return water from shallow aquifer to the root zone [mm].

The maximum net benefit is determined through a series of iterations using incremental increases in the applied irrigation water volume, until a maximum net benefit value is achieved. The optimal irrigation volume is set when this maximum net benefit is

reached. If the maximum net benefit is a positive value then irrigation is profitable, otherwise irrigation is not profitable or negatively affects the total revenue.

The end result of equations 19 to 22 is the determination of the net benefit of irrigation and the associated optimal irrigation volume to be applied over the time step of the simulation. The following flow diagram (Figure 18) is provided for illustration purposes, and provides a visual reference of the program code used in the irrigation net benefit calculation portion of the model.



**Figure 18.** Flow diagram of irrigation net benefit calculations preformed in the *IrrigEcon* model.

The schematic above presents the flow of equations used in the determination of the maximum net benefit. The variables included in the schematic represent unknown variables determined during the course of the procedure. Other variables used in equations 7 and 19 through 22, but not represented in the Figure 18, are known variables obtained directly from user supplied input files or the SWAT .sbs output file. These values have been excluded from the schematic above for the sake of simplicity.

The first step in the procedure is the calculation of the net benefit without irrigation application, referred to above as  $NB_0$ . This value differs from the net benefit without irrigation installation, which excludes the additional cost of the irrigation equipment installation and maintenance costs. The calculation of  $NB_0$  is a boundary condition that assumes the volume of irrigation water applied is zero  $m^3/ha$ , and sets the yield equivalent to actual yield without irrigation obtained directly from the SWAT output file. The value  $NB_0$  is equivalent to the expected return of having an irrigation system but not using it (i.e. the lowest possible net benefit value of irrigation).

The procedure then goes through an iterative process that incrementally increases the applied irrigation depth ( $I_D$ ) by 1 mm for each iteration. Given the new irrigation depth ( $I_{D_i}$ ), at a specific iteration, the volume of water applied ( $Vol_{I_i}$ ), based on each irrigation system, is determined, as is the new target evapotranspiration ( $ET_{I_i}$ ) and the new target yield ( $Y_{I_i}$ ). These values are then used in the calculation of the net benefit equation (19b), the output of which is compared to the net benefit value of the previous iteration ( $NB_{(i-1)}$ ), in order to determine if the maximum net benefit value has been obtained. If the net benefit value of the previous iteration is greater than the current net benefit value, the maximum net benefit and associated variables are set at the previous

iteration values. The maximum net benefit value is then calculated for each HRU and summed over the course of the year and averaged for each year.

The method described above determines the optimal economic irrigation volume to supply plant requirements, but does not take into account potentially greater alternative water uses for competing sectors of society such as residential, industrial and commercial, in cases where water supply is limited. In the case of Maryland it is assumed that water is sufficient to meet the water demand for all sectors. In the case where water is not sufficient to meet the demand of all sectors of the society, the value of water will be higher due to limited supply. This new value can be used in the equations above in order to determine a revised optimal irrigation volume. Higher water costs associated with lower supply levels or imposed government tariffs will result in the prescription of reduced irrigation quantities associated with lower yields given the model parameters above.

#### *Irrigation Water Demand:*

The next step in the model development is to define the irrigation demand as an aid to determining the irrigation schedule. The irrigation prescription component of this model generates two variables, which define the irrigation schedule for each HRU in which an economic agricultural crop is produced: the first is the irrigation volume applied at each irrigation event within a given time step, while the second is the irrigation frequency. The two are inextricably connected, and as such contain some inherent flexibility in that a series of frequencies and adjusted application quantities may be comparable in effectiveness provided that the volumes applied do not lead to runoff, deep percolation and other losses leading to decreased water use efficiency. Therefore, in

general the manipulation of one of these variables will affect the other, resulting in no net change in the irrigation application over the time step. It is possible therefore, to have frequent irrigations applying relatively small quantities of water, or conversely, one could choose relatively infrequent irrigation events applying relatively large quantities of water.

As defined in the introductory material of this report, the total plant available soil-water is the quantity of water contained within the soil of the root zone from the wilting point up to field capacity. As a general practice, irrigation is initiated once the plant available soil-water has been depleted to a predetermined set point, generally 50%. At this point irrigation is applied and the soil-water is again raised to field capacity.

The initiation of irrigation based on soil water content is mostly done due to the relative ease and simplicity of the approach. Under such criteria, a fixed quantity of irrigation water is applied at each irrigation event to bring the soil-water level from a set intervention point up to field capacity; however, the interval between irrigations may vary greatly depending upon the rate of evapotranspiration between each irrigation event. At each irrigation event a fixed quantity of water is applied, bring the soil-water content to field capacity, where it again begins to diminish until it reaches the 50% level, at which time a new irrigation event is initiated.

In the case of this study, the applied irrigation volume is linked to crop yield, through the determination of the net benefit as discussed in the previous section. Therefore, the total irrigation volume to be applied over the course of the time step is known. With this alternative approach the most straightforward means of determining an irrigation schedule is to assume a fixed irrigation interval, and apply equal portions of the total irrigation volume at each irrigation event. The irrigation quantity applied at each

irrigation event is then the total volume of water applied over the time step divided by the number of irrigation intervals within the time step, as shown in equation 23;

$$V_I = \frac{Vol_I}{[t_s / Irr_I]} \quad (23)$$

Where,  $V_I$  is the irrigation volume applied at each irrigation event [ $m^3$ ],  $Vol_I$  is the irrigation volume applied to HRU over the time step [ $m^3$ ],  $Irr_I$  is the irrigation interval between irrigation events [days] (for example 10 days between irrigation events), and  $t_s$  is the time step [days] (for example 30 days if a monthly time step is used for all reported variables listed in the SWAT output data; SWAT itself may use a daily time step in the calculation of internal variables but reports monthly totals in its output .sbs file).

This approach has the advantage of allowing the farm manager to plan irrigation events on a set time interval, and to adjust the irrigation duration as needed. This is particularly beneficial when the farm has a limited water supply capacity and a large number of irrigation valves that must be operated independently or in sequence, in order to not exceed the supply pressure capacity, or alternatively to allow for predictable rotations if the farm is using a traveling gun system where irrigation equipment must be rotated throughout the irrigated area in order to reach all segments of the field.

Although a great deal of flexibility exist with regards to the duration of the irrigation interval, it may be possible that the interval is too long or too short. Using a short irrigation interval will allow the manager to maintain a higher soil moisture content throughout the growing season, however, shorter irrigation intervals also involve longer and more frequent periods of leaf wetness, which could potentially lead to fungal growth

and poor plant health depending on the plant species; secondly applying small quantities of water could lead to inefficient distribution due to start up and shut down inefficiencies of the irrigation system being used. On the other hand, extended periods between irrigations could allow soils to dry beyond tolerable levels, resulting in plant stress followed by heavy irrigations leading to wasted water.

As a general check of the appropriateness of the irrigation interval, the soil-water level at the end of each irrigation event is determined and compared to the soil-water level at field capacity. An initial irrigation frequency of one week will be assumed and then tested against set criteria. If the final soil water level, after each irrigation event, is greater than the soil water at field capacity, then clearly, the applied volume of water is too high and the irrigation frequency must be increased in order to lessen the applied volume per irrigation event. Conversely, if the final soil-water level is too low, less than 30% of the plant available water, then the irrigation interval can be decreased to a fortnightly or monthly basis.

The applied irrigation volume calculated accounts only for irrigation events needed to replenish available soil-water levels and to meet the target evapotranspiration rate determined in a previous section. However, there may be occasions when additional irrigation events are beneficial for the purposes of soil leaching, frost protection, control of germination, blossom delay, wind erosion protection, pest management, and plant cooling (ASAE, 1990). These are all valid reasons for additional irrigation events and relate directly to good management practice, however, these irrigation events are not intended to address specifically the issue of evapotranspiration and consumptive use, and therefore are not modeled in this project, nor can they be in the absence of the unknown



or somewhat subjective parameters in which these alternatively motivated irrigation management decisions are formulated.

It is difficult, therefore, if not impossible, to assign or determine a definitive beneficial monetary value to the farmer for these management practices and added irrigation benefits. As a result, it is difficult to assess their additive value when determining the total economic benefit of irrigation; although it is clear that some additional value does exist, which is in itself, a further justification for irrigation installations. However, in order to maintain the relative simplicity of the model, irrigation will be considered only for the purpose of supplementing insufficient precipitation.

Moreover, it is assumed that in the case of Maryland, irrigation is intended only to punctuate short periods of reduced precipitation, and therefore, salt accumulation associated with poor water quality (requiring additional soil leaching) is not expected to present a significant problem, assuming fair initial irrigation water quality and soil conditions, and given the high seasonal precipitation values associated with the region. However, in practice periodic surveys of the soil salt content of irrigated fields may be required in order to substantiate this assumption.

*Total Agricultural Water Demand:*

Once the irrigation schedule is determined for each individual HRU within the area of interest, the total annual supplemental irrigation demand, needed to replenish crop evapotranspiration requirements, for the watershed of interest is computed as the summation of the total irrigation water applied to all HRU's, over a specified time period, shown in equation 24.

$$V_{WAT} = \sum_{k=1}^n \left[ \sum_{j=1}^m \left[ \sum_{i=1}^{12} V_I \left( \frac{30}{(Irr_I)_i} \right) \right]_j \right]_k \quad (24)$$

Where,  $V_{WAT}$  is the annual irrigation water demand for overall watershed [ $m^3$ ],  $V_I$  is the volume of irrigation water for a specific HRU supplied at each irrigation [ $m^3$ ],  $Irr_I$  is the number of days between irrigations [days],  $i$  is the month of the year (January – December) [month number],  $j$  is the HRU contained within subbasin  $k$  [number],  $k$  is the subbasin contained within the overall watershed [number],  $m$  is the number of HRU's within the subbasin that contain agricultural crops [number], and  $n$  is the number of subbasins within the overall watershed that contains agricultural crops [number].

Equation 24 assumes that the irrigation schedule is altered on a monthly basis, or less frequently. The equation sums the irrigation water applied for all months of the year, although an irrigation schedule is determined for only months contained within the growing season. The volume of water applied for months outside of the specified growing season is by default zero cubic meters. This is an assumption made for the simulations included in this study; however, it is possible, particularly for the southern states, to have multiple growing seasons within a give year.

Equation 24 may be broken down into three individual components to calculate the water applied annually, which include: the volume applied to each HRU; the volume applied to each subbasin, including all HRU's in which an agricultural crop is produced; and the volume applied collectively for the entire watershed. These individual components are summarized in equations 25a, 25b and 25c, respectively.

$$V_{HRU} = \sum_{i=1}^{12} \left[ V_I \left( \frac{30}{(Irr_I)_i} \right) \right] \quad (25a)$$

$$V_{SUB} = \sum_{j=1}^m (V_{HRU})_j \quad (25b)$$

$$V_{WAT} = \sum_{k=1}^n (V_{SUB})_k \quad (25c)$$

Where,  $V_{HRU}$  is the annual irrigation water demand for individual HRU [ $m^3$ ],  $V_{SUB}$  is the annual irrigation water demand for a subbasin [ $m^3$ ],  $V_{WAT}$  is the annual irrigation water demand for overall watershed [ $m^3$ ],  $V_I$  is the volume of irrigation water for a specific HRU supplied at each irrigation [ $m^3$ ],  $Irr_I$  is the number of days between irrigations [days],  $i$  is the month of the year (January – December) [month number],  $j$  is the HRU contained within subbasin  $k$  [number],  $k$  is the subbasin contained within the overall watershed [number],  $m$  is the number of HRU's within the subbasin that contain agricultural crops [number], and  $n$  is the number of subbasins within the overall watershed that contains agricultural crops [number].

*Summary of Calculation Input Data:*

The equations incorporated into the *IrrigEcon* model draw upon information from a number of sources including SWAT input and output files, and economic/irrigation system data supplied by the user. Although the sources of these variables have been identified in the discussion above, this information is summarized in Table 9 for ease of

reference. The table lists the equations and variables used, and identify the source of the information.

The data files identified in Table 9, refer to input files required by the *IrrigEcon* application that synthesizes the compiled economic and irrigation system data used in this study, as well as the output files produced by the *IrrigEcon* application and SWAT model. This information includes the cost of irrigation installations and prices received for agricultural products.

**Table 9.** Table of the irrigation-economic program component variables used and the source of the database values.

Variable:	Variable Description:	Variable Source:	Data File:	DB Variable:
<i>Variables of Equation 20: Determination of Irrigation Application Depth/Volume</i>				
Vol <sub>i</sub>	Irrigation water volume applied over the time step [m <sup>3</sup> ]	Result of Equation 20: <i>IrrigEcon</i> Output	tbl_results	t_vol_i
I <sub>D</sub>	Effective minimum irrigation depth applied over time step [mm]	Determined by multiple iterations: <i>IrrigEcon</i> Output	tbl_results	idepth_i
A <sub>HRU</sub>	Area of the Hydrologic Response Unit [km <sup>2</sup> ]	SWAT .sbs output file	.sbs	AREA
EFI	Irrigation system efficiency [dimensionless]	<i>IrrigEcon</i> Input	tbl_irrsys	irr_eff
<i>Variables of Equation 21: Determination of Net Benefit</i>				
Vol <sub>i</sub>	Irrigation water volume applied over the time step [m <sup>3</sup> ]	Result of Equation 20: <i>IrrigEcon</i> Output	tbl_results	t_vol_i
NB <sub>i</sub>	Net benefit [\$ /ha]	Maximized through multiple iterations	tbl_results	NB_i
YLD	Harvested yield [tons/ha]	SWAT output file	.sbs	YLD
P <sub>s</sub>	Sale price of yield [\$ /ton]	<i>IrrigEcon</i> Input	tbl_econ	p_crop
C <sub>p</sub>	Agricultural cost of production [\$ /ha]	<i>IrrigEcon</i> Input	tbl_econ	c_comb
C <sub>ID</sub>	Irrigation installation net depreciation for time step [\$ /ha]	<i>IrrigEcon</i> Input	tbl_irrsys	ann_dep
C <sub>w</sub>	Cost of water [\$ /m <sup>3</sup> ]	<i>IrrigEcon</i> Input	tbl_irrsys	c_water
k <sub>y</sub>	crop yield response factor [dimensionless]	<i>IrrigEcon</i> Input	tbl_econ	ky
ET <sub>a</sub>	actual evapotranspiration	SWAT .sbs output	.sbs	ET

Variable:	Variable Description:	Variable Source:	Data File:	DB Variable:
	[mm]	file		
ET <sub>t</sub>	Target evapotranspiration [mm]	Result of Equation 22 taken from: <i>Irrig.mdb</i>	tbl_results	tet_i
<i>Variables of Equation 22: Determination of Target Evapotranspiration</i>				
ET <sub>t</sub>	Target Evapotranspiration [mm]	Result of Equation 21: <i>IrrigEcon</i> Output	tbl_results	tet_i
I <sub>D</sub>	Effective minimum irrigation depth applied over time step [mm]	Result of Equation 20: <i>IrrigEcon</i> Output	tbl_results	idepth_i
PERC	Percolation past root zone [mm]	SWAT output file	.sbs	PERC
SF	Snowfall during time step [mm]	SWAT output file	.sbs	SNOFALL
SM	Snowmelt during time step [mm]	SWAT output file	.sbs	SNOMELT
LQ	Lateral flow during time step [mm]	SWAT output file	.sbs	LATQ
RVAP	Return water to root zone [mm]	SWAT output file	.sbs	REVAP
PRECIP	Precipitation falling during times step [mm]	SWAT output file	.sbs	PRECIP
SQ	Surface runoff during time step	SWAT output file	.sbs	SURQ
<i>Variables of Equation 23: Determination of Irrigation Volume at each Irrigation Event</i>				
V <sub>I</sub>	Irrigation volume applied at each irrigation [m <sup>3</sup> ]	Result of Equation 23: <i>IrrigEcon</i> Output	tbl_results	vol_i
Irr <sub>I</sub>	Days between irrigations [number]	Internally set written to <i>Irrig.mdb</i>	tbl_results	irr_day
Vol <sub>I</sub>	Irrigation water volume applied over the time step [m <sup>3</sup> ]	Result of Equation 20.	tbl_results	t_vol_i
t <sub>s</sub>	Time step [days]	Internal variable of SWAT	N/A	Set to 30 days
SOL_BD	bulk density [Mg/m <sup>3</sup> ]	SWAT soil input file	.sol	SOL_BD
<i>Variables of Equation 24 and 25: Determination of Annual Water Demand</i>				
V <sub>WAT</sub>	annual irrigation water demand for overall watershed [m <sup>3</sup> ]	Result of Equation 24: <i>IrrigEcon</i> Output	tbl_total	vol_ann
Irr <sub>I</sub>	Days between irrigations [number]	Internally set	tbl_results	irr_day
V <sub>I</sub>	Irrigation volume applied [m <sup>3</sup> ]	Result of Equation 23: <i>IrrigEcon</i> Output	tbl_results	vol_i

Centralizing this program data into an external data source has the advantage of allowing the user to update economic information as frequently as needed when more pertinent or up-to-date information is obtained. The economic information used for this project is considered to be representative of expected values at the time of this study, and is therefore, appropriate for the purposes of testing this model. However, this information may be updated or modified from time to time, depending on the year, location and circumstances in which this model is applied.

### **Environmental Impact of Irrigation:**

The final objective of this study is to evaluate the environmental impact of irrigation on a regional scale. The ability to achieve this objective is one of the advantages of using a robust, well tested, non-point source pollution model, such as SWAT. Two functions within SWAT facilitate the execution of this task. First, SWAT allows for the application of a fixed quantity of nitrogen and phosphorus on a per hectare basis, as a prescribed management operation for selected HRUs within each subbasin. The same management practices can be replicated for multiple simulations. Secondly, SWAT allows for the simulation of user-defined irrigation events for selected HRUs for each simulation. As a result SWAT allows the user to model transport processes by varying only the irrigation intensity, this allows for the direct comparison of nitrogen and phosphorus loadings into the channel networks with and without irrigation, given a fixed fertilizer schedule.

During this portion of the study, simulations for the Pocomoke watershed are conducted over a range of irrigation intensities, ranging from no irrigation to a maximum

irrigation volume, capable of supplying the potential evapotranspiration needs of all agricultural fields. The difference between actual and potential evapotranspiration can be seen as the potential demand for irrigation. When no irrigation is supplied zero percent of this demand is supplied. When the entire evapotranspiration deficit is supplied 100% of this demand is supplied.

Therefore, in order to evaluate the effects of irrigation at various intensities a series of simulations are run with varying irrigation intensities ranging from 0 – 100% of the potential irrigation demand. Irrigation intensities were set at 0, 3, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95 and 100 percent, a total set of 14 simulations, each with the same weather and input parameters. As a result, simulations will be conducted for a range of irrigation intensities from no irrigation to a maximum irrigation schedule maintaining soil-water levels at or near field capacity at all times. The variables from each simulation are then averaged over a 20-year simulation period.

In addition, two sets of irrigation simulations were run with a high and low fertilizer application rates. The initial concentration of available nutrients and the subsequent application of nitrogen and phosphorus are equivalent in all cases in both simulation sets. In each simulation fertilizer application is applied three times throughout the growing season after 15, 45, and 75 percent of the total annual heat units have been accumulated (planting occurs at 15% of the accumulated heat units).

By default SWAT allows for periodic application of fertilizer once nitrogen or phosphorus stress ensues, however, the variable application quantities between the various simulations (over a range of irrigation intensities) would not allow for direct

comparison. Therefore, equal applications of a known quantity of fertilizer are applied to meet the needs of both the irrigated and non-irrigated simulations.

The fertilizer application quantity applied in this study is based on recommendations published by the Maryland Cooperative Extension (2002) for various crops. The recommended fertilizer application rates used in this portion of the study is based on corn production, simulated for all agricultural row crops HRU's. Phosphorus recommendations are given according to initial soil fertility tests that must be conducted for each field prior to application.

Since the initial phosphorus concentrations are not known and nor available from the soil data provided by the USGS, applied phosphorus quantities for the high fertilizer application simulations correspond to recommended levels for soils with 'low' initial phosphorus concentrations, according to the Maryland Cooperative Extension (2002) recommendations. The phosphorus quantities applied for the low fertilizer application simulations correspond to the recommended application levels for soils with 'optimum' initial phosphorus concentrations.

A single application schedule of nitrogen is recommended independent of soil conditions. Therefore, during the high fertilizer simulations recommended nitrogen concentrations are applied; for the low fertilizer application simulations approximately 20% less nitrogen is applied in order to simulate nitrogen scarcity, but not over stress the plant growth. Table 10 shows applied fertilizer levels for both the high and low fertilizer application simulations.



**Table 10.** Nitrogen and phosphorus application levels for both ‘high fertilizer’ and ‘low fertilizer’ simulations.

Application Event:	Low Fertilizer Application Simulation		High Fertilizer Application Simulation	
	Nitrogen App. (kg/ha):	Mineral Phosphorus App. (kg/ha)	Nitrogen App. (kg/ha):	Mineral Phosphorus App. (kg/ha)
Application 1:	37.20	6.90	24.00	28.40
Application 2:	37.20	6.90	33.75	15.00
Application 3:	39.60	0.00	82.50	0.00
<b>Total:</b>	<b>114.00</b>	<b>13.80</b>	<b>140.25</b>	<b>43.40</b>

The initial two fertilizer applications for the low fertilizer simulations use a 31-13-00 (N-P-K) concentration fertilizer mix with an application rate of 120 kg/ha for all agricultural fields within the watershed. The third application uses a 33-00-00 fertilizer mix with an application rate of 120 kg/ha. To achieve the desired application for the high fertilizer simulations, the first applications administers 80 kg/ha of a 30-80-00 mix. The second application applies 225 kg/ha 15-15-15 mix, while the final application applies 250 kg/ha of a 33-00-00 mix.

The generic fertilizer mixes selected (31-13-00, 33-00-00, 30-80-00 and 15-15-15) indicate the relative proportion of inorganic nitrogen, phosphorus and potassium, in the form of mineral N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O, respectively (Neitsch et al., 2002b). However, only the nitrogen and phosphorus quantities are modeled in these SWAT simulations. The application of 120 kg/ha of fertilizer provides 37.2 kg/ha of mineral N, and 6.9 kg/ha of mineral phosphorus, for the first two fertilizer applications, with 39.6 kg/ha of mineral nitrogen alone being applied in the third application.

The quantity of mineral nitrogen applied is calculated as 31% of the total weight for the first two applications, and 33% of the total weight for the third application. The quantity of phosphorus applied for the first two fertilizer applications is calculated as

13% of the total weight of the applied fertilizer (120 kg/ha) times the molecular weight of the phosphorus atoms over the total molecular weight of the overall compound  $P_2O_5$  (63/142). The third fertilizer application, for the 'low fertilizer simulations' contains only mineral nitrogen as a fertilizer ingredient. The relative percentage of phosphorus contained within the generic fertilizer applied is zero resulting in no additional application of phosphorus. As a result of the three fertilizer applications, a total of 114 kg/ha of mineral nitrogen and 13.8 kg/ha of mineral phosphorus is applied over the course of the growing season for each year of the 'low fertilizer' simulations. The total application of nitrogen and phosphorus applied during the 'high fertilizer' simulations is calculated in the same manner using the generic fertilizer mixes listed above.

In reality fertilizer application and type would vary greatly between each farm depending on the preferences of the farm manager, and the needs of the particular crop and field, however, for the purpose of this simulation, a single fertilizer type and fertilizer schedule is universally applied to all fields. This allows for easy comparison between simulations.

The model output values for nitrogen and phosphorus loading within the main channel of each subbasin and for the overall simulation will be directly compared for determining the overall beneficial or detrimental environmental impact of irrigation on the watershed. This study includes only a comparison of simulated values, and will have to be verified in the field in order to determine if an actual environmental effect exists.

The accuracy of the simulation results are limited by the accuracy of the input data and grids, including elevation, land use and soils maps, as well as associated variable values and calculation procedures. However, as all calculation procedures and inputs,

including the generated weather pattern, are identical in each simulations, with the exception of the inclusion or exclusion of irrigation and the intensity thereof, any difference in nitrogen or phosphorus loading and sediment transport into the channel reaches, between simulations, can only be attributed to the presence or absence of irrigation and the associated irrigation schedule, as the sole source of variation between each simulation. Therefore, an observed difference in nutrient/sediment loading within each subbasin, or within the overall watershed, may provide a basis for conducting further field research.

Following the environmental simulations, statistical analysis is conducted on the model results using the Statistical Analysis Software, *SAS* Version 9.1 (SAS, 2005). An initial *t*-test is conducted on each variable to determine if a significant difference exists between simulations with and without supplemental irrigation. Once statistically significant variables are determined a regression analysis is conducted in order to determine the relationship between the model variables and the irrigation intensity. The best fit equation is determined by the evaluation of the R-squared value and the adjusted R-squared value.

The R-squared value is a measure of the correlation of a sample set to a regression line, and is calculated as one minus the sum of squares of the error (the summation of the squared deviation values from a model predicted value) over the sum of squares of the total (the summation of the squared deviation values from a sample set mean), as shown in equation 26a. The adjusted R-squared value adjusts the calculated R-squared value to account for multiple independent variables used in the regression analysis. The adjusted R-squared value adjusts the R-squared value by dividing the sum of squares of the error

by the degrees of freedom of the error (the sample size minus 1), and by dividing the sum of squares of the total by the degrees of freedom of the total (the degrees of freedom of the error minus the number of independent variables), as shown in equation 26b.

$$R^2 = 1 - \left[ \frac{(SS_{error})}{(SS_{total})} \right] \quad (26a)$$

$$R_{adj}^2 = 1 - \left[ \frac{(SS_{error})/(n-1)}{(SS_{total})/(n-k-1)} \right] \quad (26b)$$

Where,  $R_{adj}^2$  is the adjusted R-squared value,  $R^2$  is the R-square value,  $SS_{error}$  is the sum of squares of the error,  $SS_{total}$  is the sum of squares of the total,  $(n-1)$  is the degrees of freedom of the error,  $(n-k-1)$  is the degrees of freedom of the total,  $n$  is the number of samples, and  $k$  is the number of independent variables.

*SAS* is used to conduct a regression analysis on each of the statistically significant environmental model variables versus the irrigation intensity level. The calculated adjusted  $R$ -squared value is then used as a measure of the predictive power of the best fit equation of three model function forms: the linear equation form, the natural log form and the squared root form. The general form of the model equations are presented as equations 27a, b and c.

$$y = C_1x + C_2 \quad (27a)$$

$$y = C_1 \ln(x) + C_2 \quad (27b)$$

$$y = C_1\sqrt{x} + C_2 \quad (27c)$$

Where,  $y$  is the dependent variable (i.e. variable values determined in SWAT),  $x$  is the the independent variable (the irrigation intensity level), and  $C_1$  and  $C_2$  are the transform equation constants.

## **CHAPTER V: RESULTS AND DISCUSSION:**

### **Summary of Initial Expectations:**

At the start of this study there were three primary expected results. First, it is expected that an analytical, economic based justification of irrigation installations can be provided for a considerable portion of Maryland's agricultural land on the eastern shore. Currently, only a relatively small portion of Maryland's agricultural land (6%) is fitted with irrigation equipment. The results of this analysis show that a far larger portion of land could potentially profit from the installation of such equipment. The uncertainty associated with the prohibitive installation costs of the said irrigation equipment hinders potential farm irrigation managers from investing in such technology. At the current time farm managers have no analytical means of assessing the likelihood of achieving a return on their investment in irrigation equipment, nor do they have a means of selecting the optimal system, in term of the potential net benefit of each system, given the specific field and management conditions associated with a given farm operation. The irrigation-economic model developed within this project is intended to lessen some of the uncertainty by evaluating the risks and benefits, in order to more narrowly estimate the net benefit of such an installation, given current or anticipated market conditions.

Currently, both the average net benefit of applied irrigation and the percentage of agricultural fields that could potentially benefit from irrigation are unclear, with no means to analytically differentiate between field sites. Therefore, the current model is expected to give insight into the potential for irrigation within a temperate zone such as Maryland's eastern shore, using the Pocomoke watershed as a model test area.

Simulation runs showed great potential for profitable irrigation installations so long as water costs remained less than or equal to 10 cents/m<sup>3</sup>.

The second expectation at the start of this project is that the potential beneficial use for agricultural water is expected to be substantially higher than current consumption. By weighing the relative water demand for the Maryland region based on the current allocation of agricultural cropland for various crops, the *IrrigEcon* program prescribed significantly higher agricultural water consumption rates on a regional scale than is currently in practice. However, the prescribed water consumption dropped considerably with increasing water cost, corresponding to decreases in the models predicted net benefit values.

Evaluating irrigation water demand for a range of water cost values allows for direct comparison of the value of water for agricultural use to the value of water associated with competing sectors of society, thereby providing a basis for prioritizing the use of limited water resource supplies. The model attempts to relate the volume of water prescribed for irrigation to a tangible economic value in terms of expected net return due to increased yields, thereby determining the comparative economic value of the prescribed water allocation. This places a monetary value on the water consumed for agricultural purposes, which allows policy makers to compare the net benefit of agricultural water consumption to the value of water consumption associated with other sectors of society, in order to make informed, equitable and mutually advantageous decisions and policies regarding water consumption.

The third initial expectation is that the increased productivity of agricultural lands, in terms of yield, will lead to higher more efficient use of fertilizer inputs, resulting in a

net decrease in nutrient losses to the environment. Given the rising concern over the eutrophication of natural waters surrounding the Chesapeake Bay such a reduction would be greatly welcomed. At the time of this project little information was available with regards to the impact of irrigation on nutrient losses and transport processes on a watershed scale. At the start of this project it was hypothesized that irrigation could be used to maintain higher nutrient use efficiency values, which in turn will reduce nutrient losses.

The initial first look into the potential environmental benefit of irrigation, through the use of this model, revealed that higher yields were maintained through successive years resulting in higher nutrient efficiencies, however, export loads of phosphorus were found to increase as a result of increasing sediment loadings. Nevertheless, nitrogen export levels were found to decrease overall with simulations using irrigation. These results require field verification and lack the management considerations associated with proper irrigation scheduling and event-timing decisions that could alter or mitigate the sediment losses and associated phosphorus transport.

### **Irrigation-Economic Model:**

This tool is developed as the basis for the decision support system used to determine, not only where and under what circumstances irrigation installations are most profitable, but also which irrigation system, given user supplied information, will yield the greatest profit for a given set of input conditions and cost parameters. Although the development and operation of this tool comprises the substantial thrust of this work, only the results of the simulations are discussed here. A fuller description of the execution and operational components of the program is included in Appendix F of this document.



A limitation of the use of a large modeling area such as the Pocomoke watershed is that crop rotations carried out year by year can not be accurately reflected for all agricultural fields throughout the region of interest; and the available landuse maps obtained from the USGS are limited in their characterization of agricultural lands as ‘Agricultural Row Crops’, and ‘Pastures’, as opposed to defining specific crops or crop rotation schedules.

Therefore, as outlined in the *Methods and Procedures* section, a series of simulations have been conducted, using the major row crops produced in Maryland according to the Maryland Agricultural Statistical Service (MASS, 2004). These crops include: corn, soybean, sorghum and wheat, which comprise the substantial majority of agricultural cropland in Maryland.

In each simulation, the same crop is grown in all agricultural fields throughout the Pocomoke. The primary advantage of this approach is that each crop is simulated or exposed to the full spectrum of field drainage conditions, elevations, soil types and climatic conditions found in the Pocomoke region. This approach, where all crops included in the study are exposed to the same set of conditions, allows for direct comparison between simulations, and ensures that all crop types are simulated under the same soil and field conditions.

#### *Corn Production:*

Corn is the most commonly produced crop in Maryland and the most significant in terms of overall production value, with nearly 40% of Maryland’s agricultural row-cropland (480 out of 1185 thousand acres of agricultural production cropland being devoted to its production in 2003 (MASS, 2004). The total crop production for this same

year exceeded 1,000,000 metric tons (50,000,000 bushels) or 7.7 metric tons per hectare (123 bushels per acre), with a total production value of nearly 140,000,000 dollars or 835 dollars per hectare (338 dollars per acre), given the average seasonal price of \$108 per metric ton (\$2.85 per bushel). These figures vary from year to year but are roughly comparable; the average production over a 6-year period (from 1998 to 2003) is 7.2 metric tons per hectare (115 bushels/acre), with an average production value of 690 dollars per hectare (278 dollars per acre).

Compared with actual values for Maryland, reported by MASS (2004), SWAT simulation results, which reportedly reflect the growth and yield rates of a generic corn variety, were significantly lower than actual values obtain by Maryland farmers. Initial model simulation yields averaged 3.63 metric tons per hectare (60 bushels per acre). This average is the average of all HRU growing corn without irrigation using a randomly generated weather pattern and averaged over a 20-year period.

This discrepancy may be the result of differences in the physical descriptive parameters included in the default SWAT crop data file, which may not be reflective of the hybrid crop varieties used throughout Maryland. Therefore, for the purposes of this simulation, the harvest index variable (HVSTI) and the lower limit harvest index (WSYF), the variable used to determine the amount of above ground biomass counted as yield, were modified to better reflect actual yields seen in past years. HVSTI and WSYF values were increased 30 percent in order to better reflect actual yields received by Maryland farmers, as reported by MASS (2004). The resulting yields without irrigation better reflected the mean actual yield (within 10-15%) obtained by Maryland farmers

over successive years. The discussion that follows reflects the data obtained from the model simulations using the calibrated crop yield coefficients.

*Soybean Production:*

A close second to corn production, in terms of the percentage of agricultural land used, is soybean production. A total of 175 thousand hectares (430 thousand acres) were devoted to soybean production in 2003 (MASS, 2004), which accounts for over 36% of agricultural crop production land in Maryland. Soybean production yielded a total of 433 metric tons (15,910 bushels) in 2003 averaging 2.5 metric tons per hectare (37 bushels per acre). Given the average seasonal price of \$265 per metric ton (\$7.25 per bushel) yields a total state production value of \$115,315,000 for the year, averaging \$660 per hectare (\$268 per acre).

*Wheat Production:*

A distant third in terms of production is wheat, with 67 thousand hectares (165 thousand acres) or 14% of Maryland agricultural cropland being devoted to its production in 2003 (MASS, 2004). The average production for the five year period from 1998 to 2002 is 4.1 metric tons per hectare (61.4 bushels per acre) fetching a seasonal average of \$115 per metric ton (\$3.15 per bushel) for the years 2002. Wheat yields for 2003 were the lowest since 1979, averaging at 2.5 metric tons per hectare (37 bushels per acre), due to unusually high rains/flooding and the spreading of disease, therefore production values for the year 2003 were not included in the average calculated above.

### *Sorghum Production:*

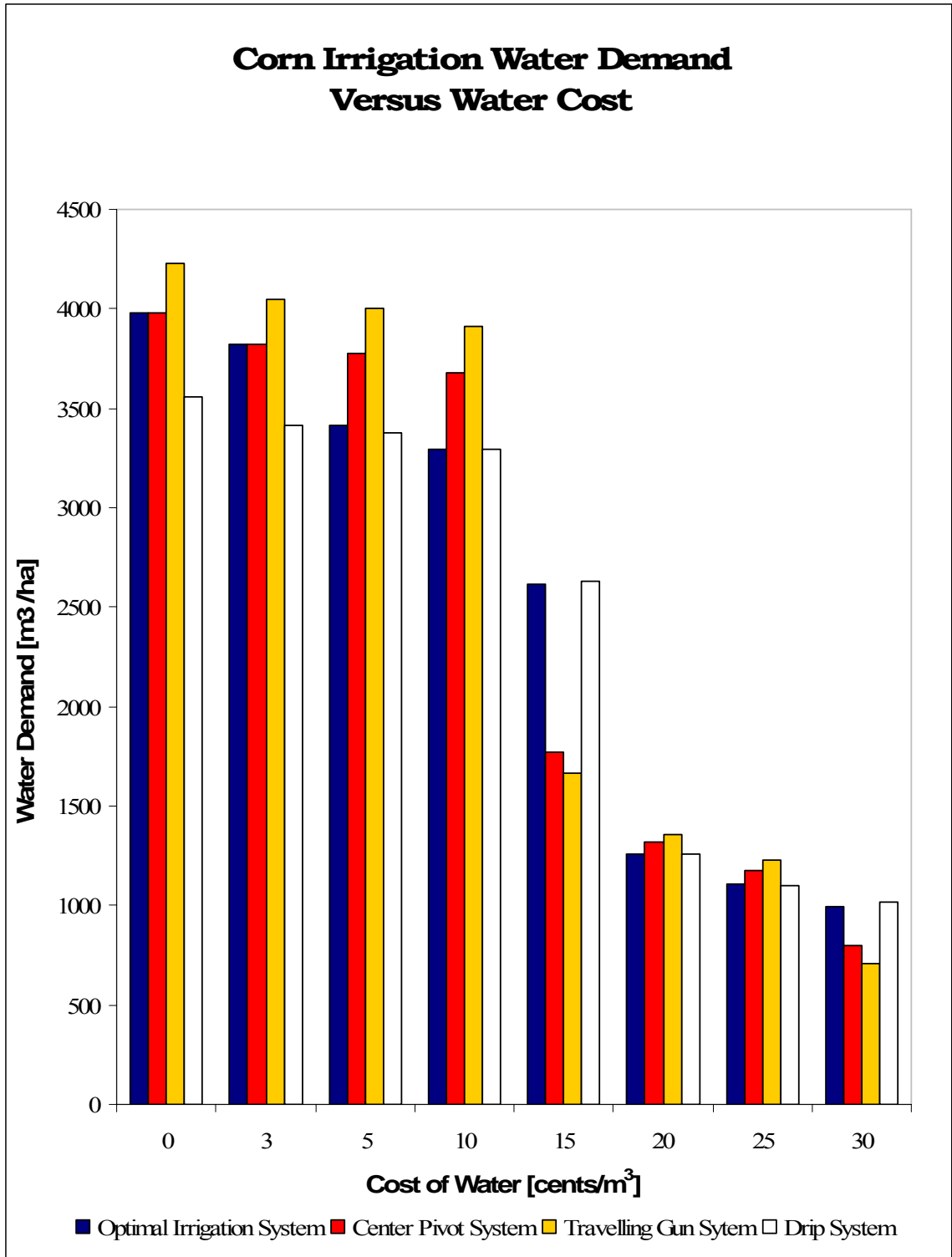
Of the crops being compared the least significant in terms of agricultural production in Maryland is sorghum. In Maryland only 1.2 thousand hectares (3000 acres) were devoted to sorghum production in 2003, with an average production of 3.3 metric tons per hectare (52 bushels per acre) for the years 2002 and 2003 (MASS, 2004). Given an average seasonal price of \$100 per metric ton (\$2.55 per bushel), yields an average production value of \$330 per hectare. Of the four crops compared sorghum remains the least valuable in terms of anticipated revenue for Maryland farmers, and the least commonly grown.

The combined production of the four crops summarized above represents nearly 80% of Maryland's agricultural cropland. Together these four crops can be categorized as the primary crop staples of Maryland agricultural, and are, therefore, the crops considered in this study. Other common agricultural crops include hay, potato, tobacco and a variety of vegetables. Most of these can not be modeled in this study due to a lack of information in regards to the crop yield response or  $k_y$  factors. These crops represent the minority in terms of Maryland production agriculture, however, the model analysis and analytical procedures employed in this study could be equally applied to these crop types should sufficient information become available. The sections that follow therefore discuss only the four staple crop types summarized above.

## **Irrigation Economics and Net Benefit:**

### *Optimal Irrigation Water Demand and Irrigation Scheduling:*

Figure 19 comparatively displays the water demand associated with each irrigation system at water cost levels varying between 0 and 30 cents per cubic meter. Also included in this figure is a plot of the average optimal water demand, for all HRUs within the watershed over the 20-year simulation period. This value represents the irrigation water demand per year for the most optimal irrigation system as determined by the *IrrigEcon* application based upon the calculated net benefit associated with each individual HRU.



**Figure 19.** Irrigation water demand versus water cost levels for corn production associated with each irrigation system.

Results depicted in Figure 19 show that the overall water demand reduces several fold when the water cost is increased to the highest water cost level (30 cents per cubic meter), when compared to the lower water cost levels (less than 10 cents per cubic meter). At the highest water cost levels, little to no economic benefit is achieved when irrigation water is applied. As a result only a few HRU's benefit from irrigation application, and even then, only infrequently and at the most critical periods when the evapotranspiration demand is the greatest; consequently water application remains at or below 1000 cubic meters per hectare annually at the highest water cost level.

At water cost levels below 10 cents per cubic meter, water demand is near the maximum levels required to substantially satisfy the evapotranspiration demand needed to achieve maximum yield. The total water demand varies with the efficiency of the system, whereby the least efficient system (the traveling gun system in this simulation) requires the greatest amount of water, while the most efficient system (drip irrigation in this case) requires the least amount of water.

At higher water cost levels water demand is minimal for all irrigation systems resulting in little variation in total demand between the three systems. As water cost levels increase, the more efficient drip system is more often recommended due to the added value in water conservation achieved over the less efficient center pivot and traveling gun systems. However, as the price of water continues to increase, the application of water no longer becomes profitable, therefore, drip irrigation, being the more expensive system, in terms of monthly overhead costs, is no longer recommended, as irrigation application as a whole is no longer prescribed. The value of the drip irrigation system is realized through water savings when the system is in operation, when

compared to the less efficient alternatives; however, this value is lost once the system is no longer used.

The graphical information presented in Figure 19 is presented below in tabular form, together with net benefit values discussed more thoroughly in a subsequent section. Table 11 is presented in order to compare water demand levels directly with calculated net benefit values, and to better distinguish between the water demand values for each of the irrigation system categories, particularly at the higher water cost levels where only slight variations in water demand are observed.

**Table 11.** Irrigation water demand and net benefit values associated with corn production for each irrigation system at various water cost levels.

Cost of Water [cents/m <sup>3</sup> ]:	Optimal Irrigation System		Center Pivot System		Traveling Gun System		Drip Irrigation System	
	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ /ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ /ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ /ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ /ha]:
\$0.00	3983	692.3	3983	692.3	4232	688.8	3561	675.1
\$0.03	3818	575.6	3818	575.6	4045	564.9	3416	570.4
\$0.05	3414	502.7	3773	499.7	4000	484.5	3378	502.4
\$0.10	3294	336.2	3681	314.6	3911	288.1	3293	336.1
\$0.15	2616	173.7	1774	152.9	1669	133.4	2633	173.6
\$0.20	1257	91.3	1322	78.9	1359	59.1	1258	90.7
\$0.25	1108	31.7	1174	16.7	1225	-5.1	1104	31.2
\$0.30	997	-21.3	800	-36.5	711	-53.8	1018	-22.1

It should be noted that the irrigation water demand associated with the ‘optimal irrigation system’ does not necessarily correspond to the system with the lowest water demand, but rather the optimal irrigation system is selected based upon which system results in the greatest overall net benefit as will be discussed further in the section below. Likewise, it should be noted that the lowest water demand is not necessarily associated with the system with the greatest distribution efficiency, which in this case is drip



irrigation. Rather water demand is correlated with the irrigation application intensity that will result in the greatest net benefit.

Data in Table 11 show that water cost levels above 10 cents/m<sup>3</sup>, the optimal water demand level is greatest for drip irrigation, indicating that the irrigation level prescribed for this system is higher than that of the alternative systems due to the greater value obtained from the more efficient drip irrigation when compared to alternate systems; as a result irrigation events are prescribed more frequently. Table 11 also shows that at water cost levels greater than 15 cents per cubic meter the drip irrigation systems emerges with the highest net benefit value, while the total water demand for each of the systems remains relatively similar.

In addition, simulation results show that at water costs levels less than 10 cents/m<sup>3</sup>, irrigation water demand is maximized, and is largely determined by the evapotranspiration demand of the crop as opposed to being curtailed by prohibitive water application costs. Under such conditions the system associated with the lowest irrigation water demand is drip irrigation. Each of the three systems applies the maximum volume of water in order to meet the entire evapotranspiration demand of the crop required to achieve maximum growth/yield. The associated water demand, required in order to meet the evapotranspiration demand of the crop, for the center pivot and traveling gun irrigation systems are greater due to their lower application efficiencies when compared to drip irrigation.

As the water cost level increases, the irrigation system associated with the highest irrigation water demand is drip irrigation as opposed the other systems with lower water application efficiencies. At higher water cost levels (above 15 cents per cubic meter)

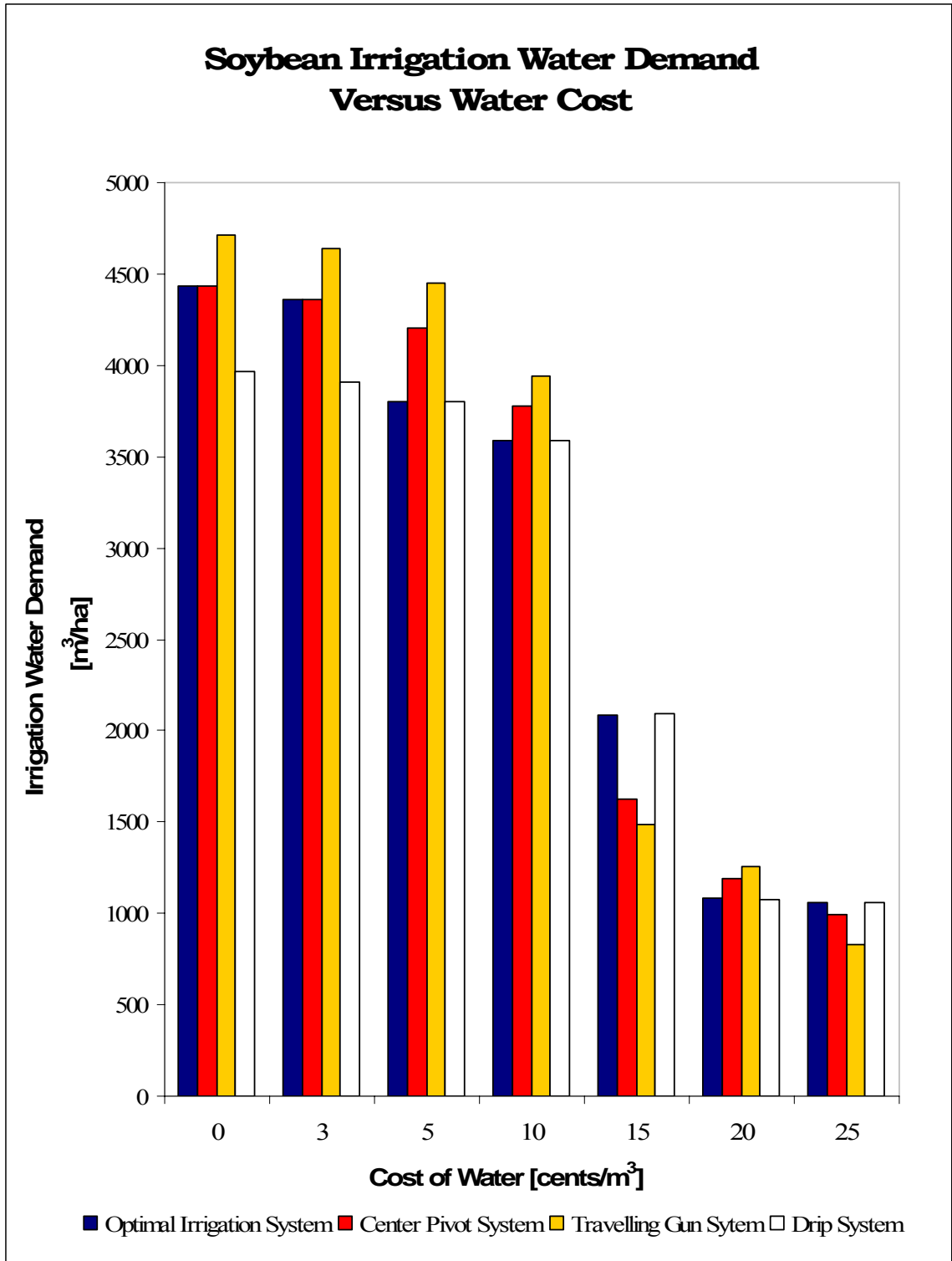
irrigation installations are more often not recommended, and for the less frequent instances when irrigation is recommended, drip irrigation is the preferred system. The resultant shift, to drip irrigation, which is associated with the highest application efficiency, results in greater water demand due to the higher frequency of irrigation application, when compared to the center pivot and traveling gun systems. The shift to drip irrigation is driven largely by the economic savings achieved through water conservation measures associated with the more efficient system (drip irrigation); the higher frequency of irrigation is a result of the greater value of water application through drip irrigation when compared to the more wasteful/less efficient alternatives.

In the later case the relative irrigation water demand increases for the system associated with the highest water use efficiency as the benefit derived per unit of water is maximized when compared to the less efficient more wasteful systems. As a result of the high water cost, water application is prescribed sparingly and only when the greatest benefit can be derived. Because water is used more effectively with the drip irrigation system, greater benefit is derived there from per unit of water applied. Therefore, the highest optimal irrigation water demand, at higher water cost levels, is associated with the drip irrigation system as this is the system deriving the greatest benefit per unit of water applied. This remains true until such time as irrigation ceases to be recommended due to exorbitant water costs.

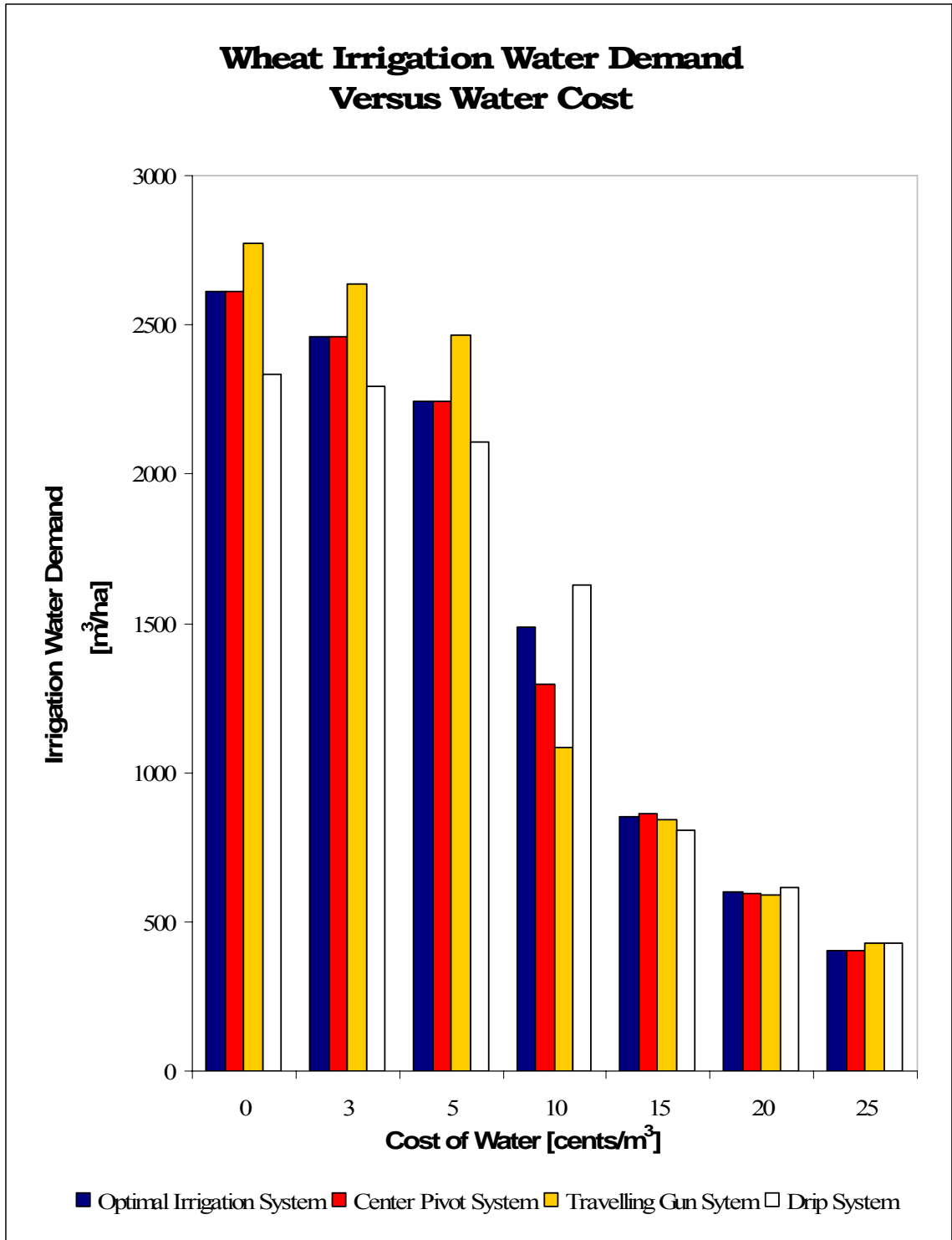
Figures 20, 21, and 22 present the irrigation water demand versus water cost curves for soybean, wheat and sorghum, respectively. In each case, similar trends appear in that each call for high water application levels when water costs are low; followed by a

rapid decline in applied water levels after a given point; followed by an apparent leveling off in the applied water volumes at higher water cost levels.

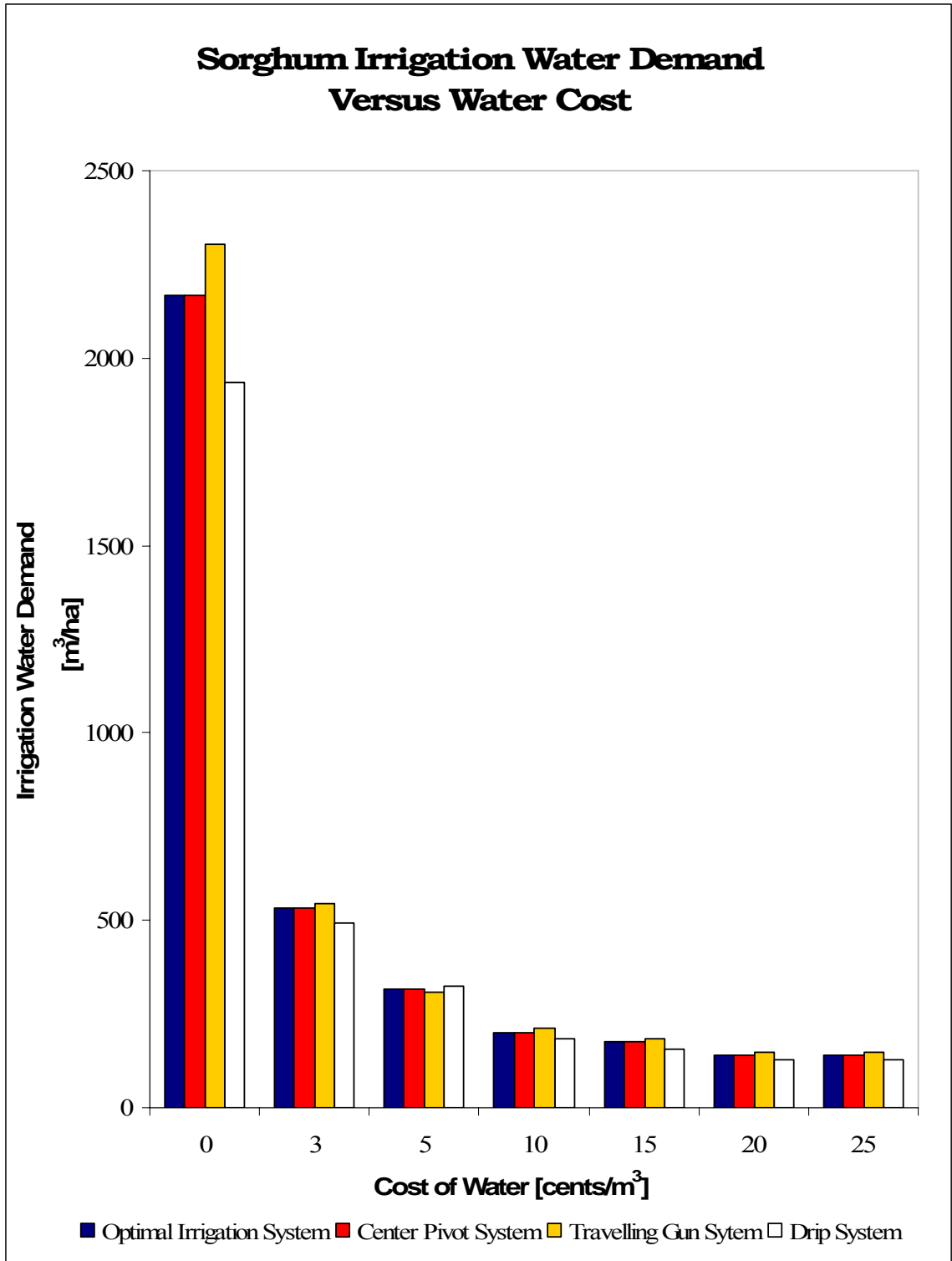
The irrigation water demand curve for soybean is similar to that of corn in that high water application levels are prescribed at water costs of 10 cents/m<sup>3</sup> or less, followed by a rapid decline in recommended irrigation levels above this cost bracket. In contrast, high water application levels are recommended for sorghum only in the case when water is free. In all other cases, where there is an associated cost to the irrigation water, the recommended water application levels rapidly decline, even at relatively low water cost levels, such as 3 and 5 cents/m<sup>3</sup>. Recommended water application for wheat rapidly declines above a water cost level of 5 cents/m<sup>3</sup>.



**Figure 20.** Irrigation water demand versus water cost levels for soybean production associated with each irrigation system.



**Figure 21.** Irrigation water demand versus water cost levels for wheat production associated with each irrigation system.



**Figure 22.** Irrigation water demand versus water cost levels for sorghum production associated with each irrigation system.

Such contrast is reflective of the combination of two characteristics: first, the relative value of the crop per unit of yield; and second, the crop yield response to water application as reflected in the crop yield response factors ( $k_y$ ) values. In this case, corn and soybean are both relatively valuable crops, 112.00 \$/metric ton for corn and 266.00 \$/metric ton for soybean (2.85 \$/bushel for corn and 7.25 \$/bushel for soybean), and therefore yield higher returns per unit increase in production. Note that despite the relatively low value of corn compared to soybean, corn remains a more productive system in terms of yield per hectare than does soybean and therefore of comparable or greater overall. Moreover, corn had the highest crop yield response factor value, 1.25 compared to 0.85 for soybean, 0.90 for sorghum, and 1.00 for wheat.

Tables 12 to 14 present the water demand versus water cost data together with net benefit values for soybean, wheat and sorghum, respectively. This information is presented in order to directly compare water demand with expected net benefit values.

**Table 12.** Irrigation water demand and net benefit values associated with soybean production for each irrigation system at various water cost levels.

Cost of Water [cents/m <sup>3</sup> ]:	Optimal Irrigation System		Center Pivot System		Traveling Gun System		Drip Irrigation System	
	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$ha]:
\$0.00	4434	654.63	4434	654.63	4711	651.14	3967	637.42
\$0.03	4363	522.05	4363	522.05	4636	510.39	3908	518.64
\$0.05	3803	440.72	4205	435.44	4451	418.82	3798	440.58
\$0.10	3587	256.21	3776	231.48	3939	204.53	3588	256.14
\$0.15	2089	100.69	1628	85.67	1489	67.57	2091	100.58
\$0.20	1081	29.67	1187	20.41	1259	2.09	1074	28.4
\$0.25	1062	-23.91	991	-37.43	832	-55.59	1060	-24.88

**Table 13.** Irrigation water demand and net benefit values associated with wheat production for each irrigation system at various water cost levels.

Cost of Water [cents/m <sup>3</sup> ]:	Optimal Irrigation System		Center Pivot System		Traveling Gun System		Drip Irrigation System	
	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:
\$0.00	2610	288.94	2610	288.94	2774	285.46	2336	271.73
\$0.03	2458	210.63	2458	210.63	2635	202.25	2294	201.66
\$0.05	2242	158.42	2242	158.42	2464	146.78	2108	154.95
\$0.10	1486	44.31	1298	42.38	1084	31	1629	43.08
\$0.15	852	-5.54	862	-5.71	842	-17.1	809	-8.87
\$0.20	599	-41.79	595	-41.91	592	-52.49	614	-45.42
\$0.25	405	-66.3	405	-66.33	428	-76.13	427	-72.43

**Table 14.** Irrigation water demand and net benefit values associated with sorghum production for each irrigation system at various water cost levels.

Cost of Water [cents/m <sup>3</sup> ]:	Optimal Irrigation System		Center Pivot System		Traveling Gun System		Drip Irrigation System	
	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:	Water Demand [m <sup>3</sup> /ha/year]:	Net Benefit [\$/ha]:
\$0.00	2168	-0.82	2168	-0.82	2302	-4.3	1935	-18.05
\$0.03	532	-41.62	532	-41.62	545	-46.14	492	-57.05
\$0.05	316	-50.4	316	-50.4	309	-54.89	324	-65.72
\$0.10	202	-62.34	202	-62.34	214	-67.08	184	-77.39
\$0.15	175	-71.63	175	-71.63	186	-76.75	157	-86.07
\$0.20	141	-79.32	141	-79.32	150	-84.57	126	-93.56
\$0.25	141	-86.38	141	-86.38	150	-92.07	126	-99.87

Table 12 through Table 14 show that soybean production is associated with the highest water volume application, varying from 4434 m<sup>3</sup>/ha·yr to 1062 m<sup>3</sup>/ha·yr for the various water cost levels modeled; while sorghum is associated with the least amount of recommended irrigation, varying from 2168 m<sup>3</sup>/ha·yr to 141 m<sup>3</sup>/ha·yr depending on the water cost level. The model recommended volume of applied water is a factor of both the physiological characteristics of the crop in terms of crop yield response and the economic value of the return in yield. The economic return is seen to be the highest at

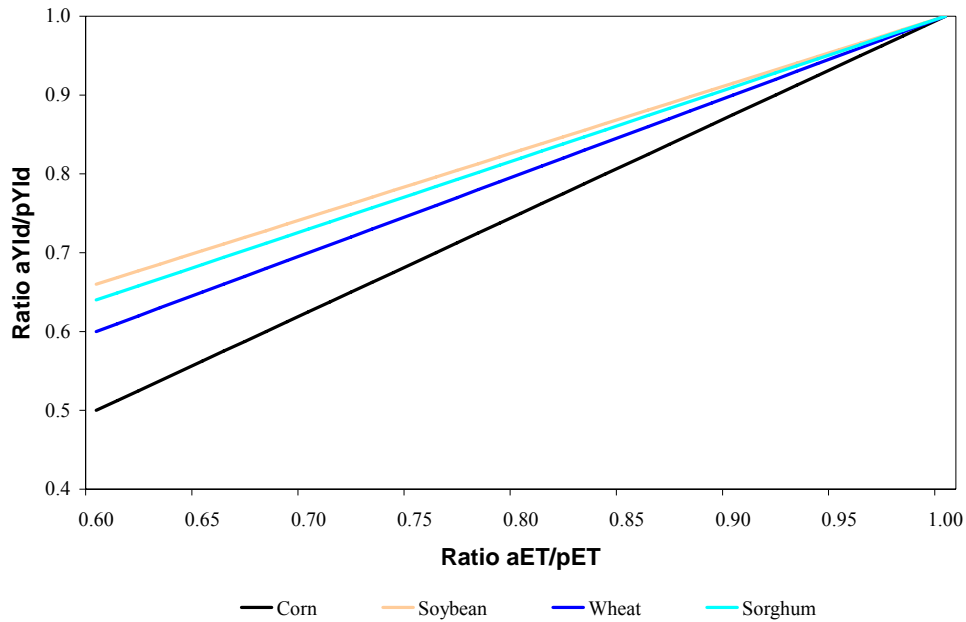


the lowest water cost levels, but drops significantly, and even becomes a deficit value, at higher water cost levels, the degree of which varies with each crop.

A comparison of Table 11 through Table 14 indicates that irrigation water demand is greatest for soybean in more instances than for any other crop. A comparison of the net benefit values indicates irrigation is more profitable for corn although soybean is associated with greater water demand. When compared on a field to field basis for the simulations conducted, irrigation is recommended for 95.0 % of the simulations involving corn, while only 83.4 % of the simulations involving soybean are recommended for irrigation.

The optimal irrigation volume to be applied to soybean, resulting in the maximum net benefit, is greater than the optimal volume of water to be applied to agricultural fields in which corn is grown. This is reflected in the crop response factors associated with the two crop types. Corn is associated with a seasonal crop response factor of 1.25, indicating a more rapid increase or decrease in actual yield compared to maximum yield for an incremental increase or decrease in actual evapotranspiration when compared to that of soybean, which is associated with a crop response factor of 0.85. As a result, a greater volume of water is required to produce an equivalent increase in soybean production when compared to corn. Figure 23 graphically demonstrates this point by plotting the ratio of actual to potential yield ( $aYld/pYld$ ) versus the ratio of actual to potential evapotranspiration ( $aET/pET$ ).

### Ratio of Actual Yield to Potential Yield Verses Evapotranspiration



**Figure 23.** Comparison of the ratio of actual to potential yield to the corresponding ratio of actual to potential evapotranspiration

The correlation is determined by the irrigation deficit equation presented as equation 7. In the case of corn ( $k_y = 1.25$ ), a 40% reduction in the actual evapotranspiration to the potential evapotranspiration ( $aET/pET = 0.60$ ) results in a 50% decrease in the potential yield ( $aYld/pYld = 0.50$ ); whereas an equivalent reduction in the evapotranspiration rate of soybean or sorghum ( $k_y = 0.85$  and  $0.80$ , respectively) results in an approximately 35% reduction in yield ( $aYld/pYld = 0.66$  and  $0.64$ , respectively). Consequently, a higher return in terms of yield can be expected for the irrigation of corn compared to sorghum or soybean. When sorghum and soybean are compared, it is observed that soybean is associated with a higher net benefit with irrigation, despite comparable  $k_y$  values, due to the higher cash value of soybean when compared to sorghum.

In general terms, the overall irrigation water demand associated with each irrigation system decreased as the cost of water increased. This downward shift, with increasing water costs, is seen with each of the three irrigation systems when independently analyzed, however, each system varied slightly in degree, depending on the efficiency and cost of the system.

At water cost levels above 15 cents/m<sup>3</sup>, little difference is seen in the water demand between the three systems, as water application is, in general, not recommended by the irrigation economic model, due to the prohibitive cost of water. However, at lower water cost levels greater variation is observed in the overall water demand, between the three irrigation systems, depending on the water use efficiency of each system.

*Net Benefit Calculations and Irrigation System Selection:*

Model simulations were run over a range of water cost values in order to define trends and present net benefit values of irrigation at various water cost levels. The results show that lower water cost levels (less than 10 cents/m<sup>3</sup>) the greater majority of agricultural lands would profit from the installation of irrigation equipment. At a water cost level of three cents per cubic meter of water, the minimum estimated water cost needed to cover the expense of delivery and distribution of irrigation water from an on site well, the average net benefit for all HRU's is estimated to be \$275 per hectare. This value is above the expected revenue without irrigation equipment (assuming crop prices received in 2003).

This net benefit value reflects the average value for all HRU's within the simulation run over a 20-year period, with a randomly generated weather pattern reflecting typical conditions associated with Maryland's eastern shore. Model

simulations indicate that at this cost level 170 out of 177 agricultural HRU's would profit from the installation of irrigation equipment, lending strong support for the wide spread use of irrigation in temperate Maryland. Table 15 through Table 17 compare the net benefit of agricultural production with and without irrigation for corn, soybean, wheat and sorghum with each of the three irrigation systems compared.

**Table 15.** Net benefit comparison with and without center pivot irrigation at a water cost level of 3 cents/m<sup>3</sup>.

Crop:	Net Benefit without Irrigation [\$/ha/yr]:	Net Benefit with Irrigation [\$/ha/yr]:	Added Net Benefit of Irrigation [\$/ha/yr]:
Corn	580.3	813.6	233.3
Soybean	899.3	1139.7	240.4
Wheat	502.6	611.0	108.4
Sorghum	68.4	63.8	-4.6

**Table 16.** Net benefit comparison with and without traveling gun irrigation at a water cost level of 3 cents/m<sup>3</sup>.

Crop:	Net Benefit without Irrigation [\$/ha/yr]:	Net Benefit with Irrigation [\$/ha/yr]:	Added Net Benefit of Irrigation [\$/ha/yr]:
Corn	580.3	809.2	228.9
Soybean	899.3	1134.9	235.6
Wheat	502.6	607.4	104.8
Sorghum	68.4	63.5	-4.9

**Table 17.** Net benefit comparison with and without drip irrigation at a water cost level of 3 cents/m<sup>3</sup>.

Crop:	Net Benefit without Irrigation [\$/ha/yr]:	Net Benefit with Irrigation [\$/ha/yr]:	Added Net Benefit of Irrigation [\$/ha/yr]:
Corn	580.3	819.1	238.8
Soybean	899.3	1145.8	246.5
Wheat	502.6	615.2	112.6
Sorghum	68.4	62.4	-6.0

Multiple model simulations were run, incrementally increasing the cost of water with each successive run. At low water cost levels (less than 10 cents/m<sup>3</sup>) nearly all HRU's were associated with a strong positive net benefit value, however this number decreased gradually with increasing water costs until finally only those HRU's associated

with the greatest economic net benefit continued to profit from the installation of irrigation equipment.

In an attempt to determine the dominant characteristics that favor irrigation installations an analysis of variance (ANOVA) was conducted using *SAS* to contrast and compare the characteristic properties associated with those HRU's found to profit from irrigation installation and those that did not. In this analysis the data from all simulations were compiled into a single data source and each HRU was categorized as either profiting from irrigation installations, labeled as 'recommended,' or those that did not profit from the irrigation installation, 'labeled as 'not-recommended.' This categorization distinguishes those areas where the net benefit associated with the HRU is or is not greater with irrigation than without irrigation for at least one of the three irrigation system included in this study.

The data is compiled from all simulations at each water cost level. As a result the greater majority of the HRU's are marked as 'recommended' for irrigation at lower water cost levels, while being categorized as 'not-recommended' at higher water cost levels. The HRU's associated with the strongest characteristics favoring irrigation installations were categorized as being recommended for irrigation at all water cost levels.

Included in this analysis of variance are such factors as: the soil properties of the top two soil layers associated with the soil type of each HRU, including the clay, silt and sand content, the soil layer depth, the hydraulic conductivity, and the available soil water content; the elevation data associated with each subbasin including the minimum, maximum and mean elevation; and the data contained within the initial SWAT output

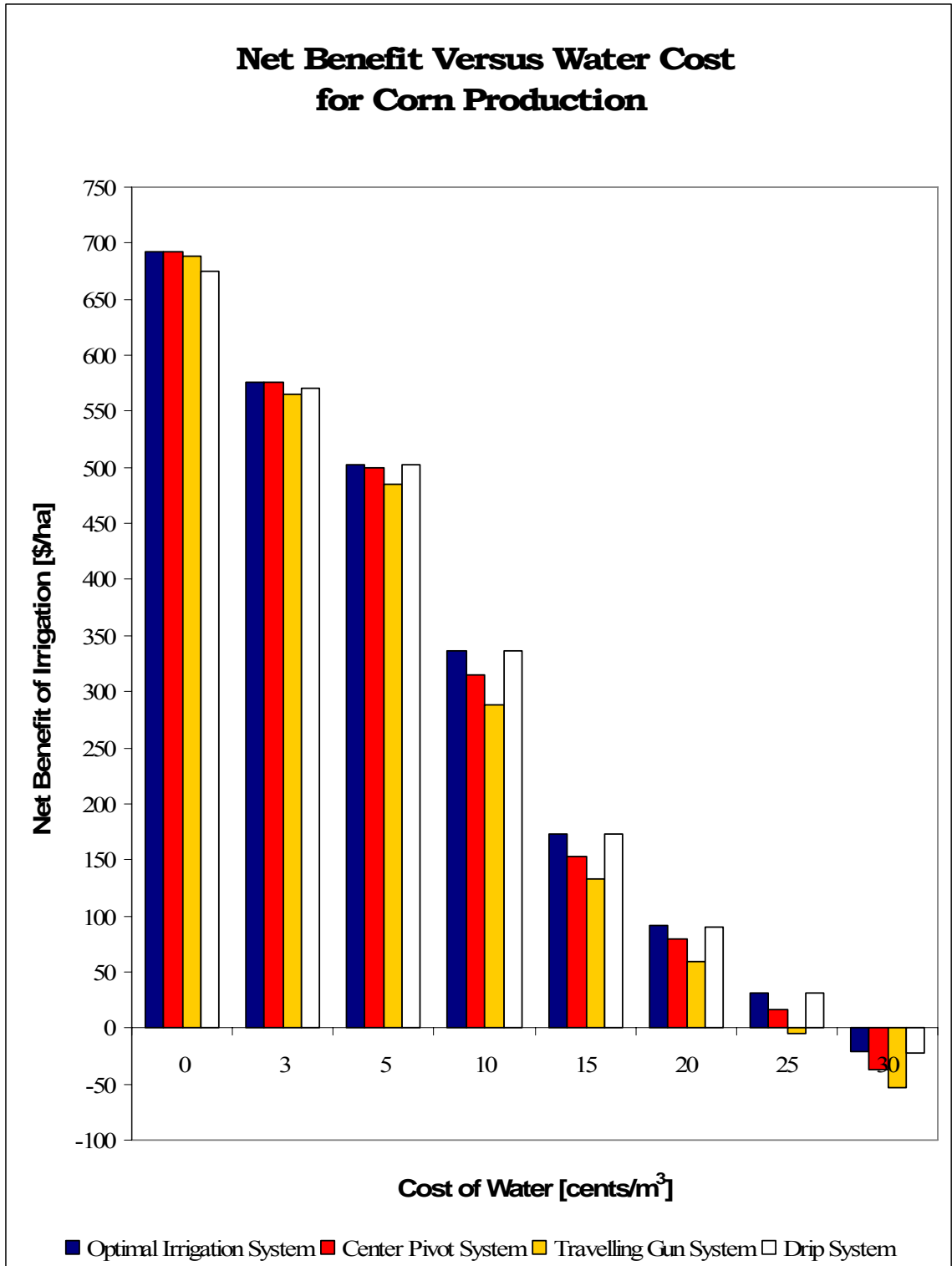
.sbs file, including the precipitation, runoff, infiltration and water content levels associated with each HRU.

Figure 24 compares the net benefit of each of the three systems, with the optimal or recommended irrigation system corresponding to the irrigation system with the highest net benefit for the particular conditions associated with each HRU. The overall net benefit of irrigation varied little between each of the three systems, with each system following the same trend at nearly the same magnitude. The magnitude of the difference in the net benefit of each system begins to widen as the cost of water increases.

Figure 24 plots the annual net benefit (dollars per hectare) versus the cost of water for the corn simulation; net benefit comparisons for other crops are presented later in this section. The figure shows strong favorable conditions for irrigation installations when water costs remain low; however, as the water cost increases to 15 cents per cubic meter and beyond, irrigation is no longer favorable for any of the three irrigation systems included in the study. The negative net benefit values associated with the highest water cost levels indicate a negative return for farmlands with the economic burden of irrigation equipment.

The data presented in Figure 24 is presented previously in tabular form in Table 11 together with the corresponding water demand values. The net benefit value for each system represents the average calculated value over a 20-year simulation when all HRU's are using the same irrigation system. The net benefit associated with the optimal irrigation system is the average calculated net benefit when the decision support component of the model selects the optimal irrigation system for each HRU.

In this case the net benefit value associated with the optimal system is equal to or greater than the highest of the average net benefit values associated with the three irrigation systems being compared. The net benefit of the optimal system is greater than that of the three individual systems when the *IrrigEcon* application recommends a particular irrigation system for one HRU and another system for another HRU, in response to the specific conditions associated with each HRU that favor one system over another. In this case, the net benefit associated with the optimal system is the average of the highest net benefit of the three systems for each HRU as determined on an individual basis.



**Figure 24.** Irrigation system comparison of net benefit versus water cost associated with corn production.



In the case of corn production, under the simulation conditions used in this study the center pivot system is found to be most economically favorable for all HRU's when the associated water cost remains below 3 cents/m<sup>3</sup>. For the mid to high range of water cost levels the most economically favorable system varied between drip and center pivot for each HRU. Therefore, the average net benefit for the optimal system is higher than the individual values of the three irrigation systems when viewed separately.

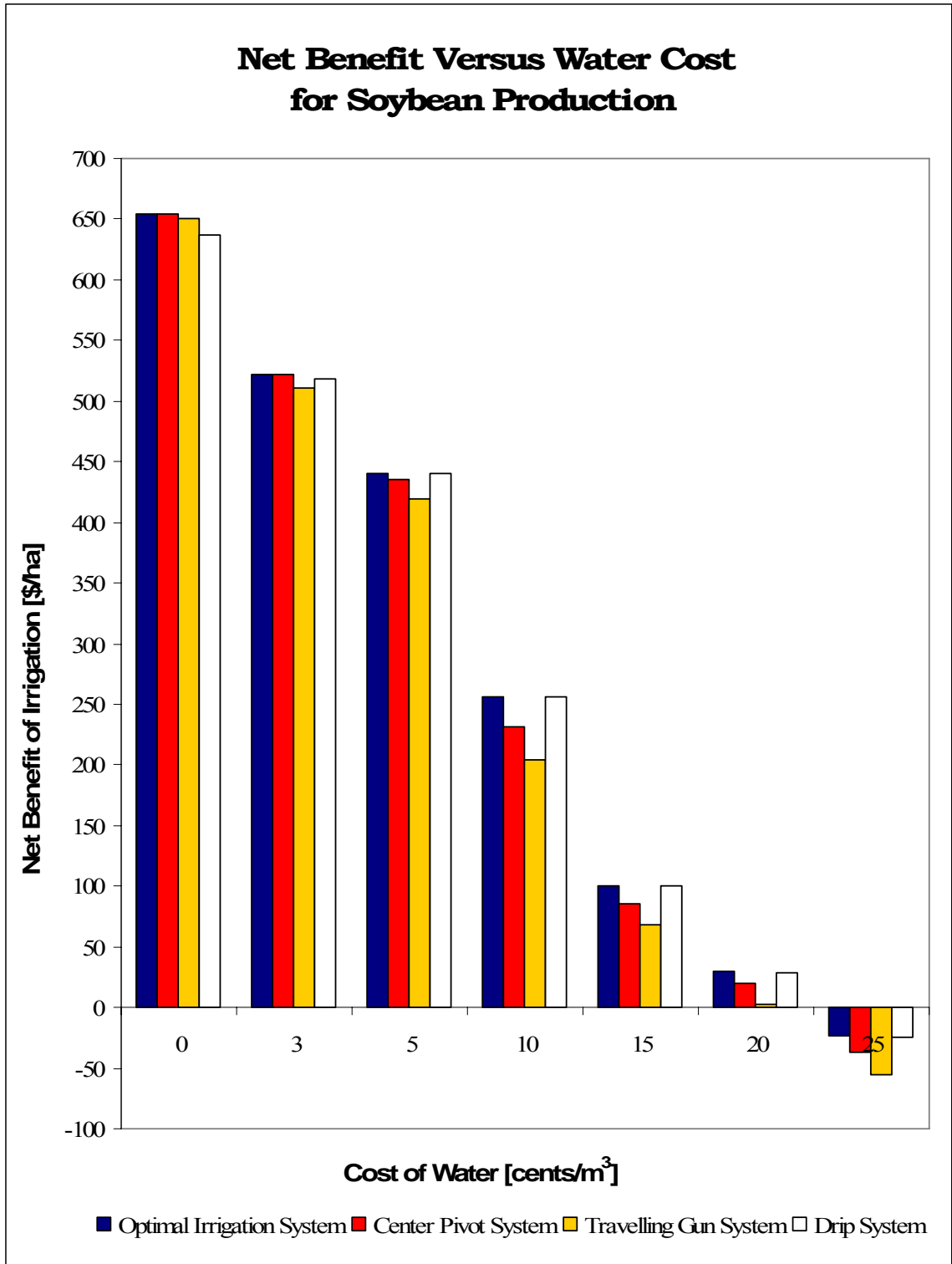
Looking closely at the data above the center pivot system is found to be the most cost effective system for each HRU when water costs are low (below 5 cents/m<sup>3</sup>). However, as the water cost increases (greater than 5 cents/m<sup>3</sup>) drip irrigation emerges as the most economically favorable system. Above a water cost level of 25 cents/m<sup>3</sup> irrigation is no longer economically beneficial for any system as indicated by the negative net benefit values.

Figures 25, 26 and 27 present the net benefit versus water cost for soybean, wheat and sorghum production, respectively. The data contained in each of these figures is presented previously in Tables 12, 13, and 14 together with the corresponding water demand values for soybean, wheat and sorghum, respectively.

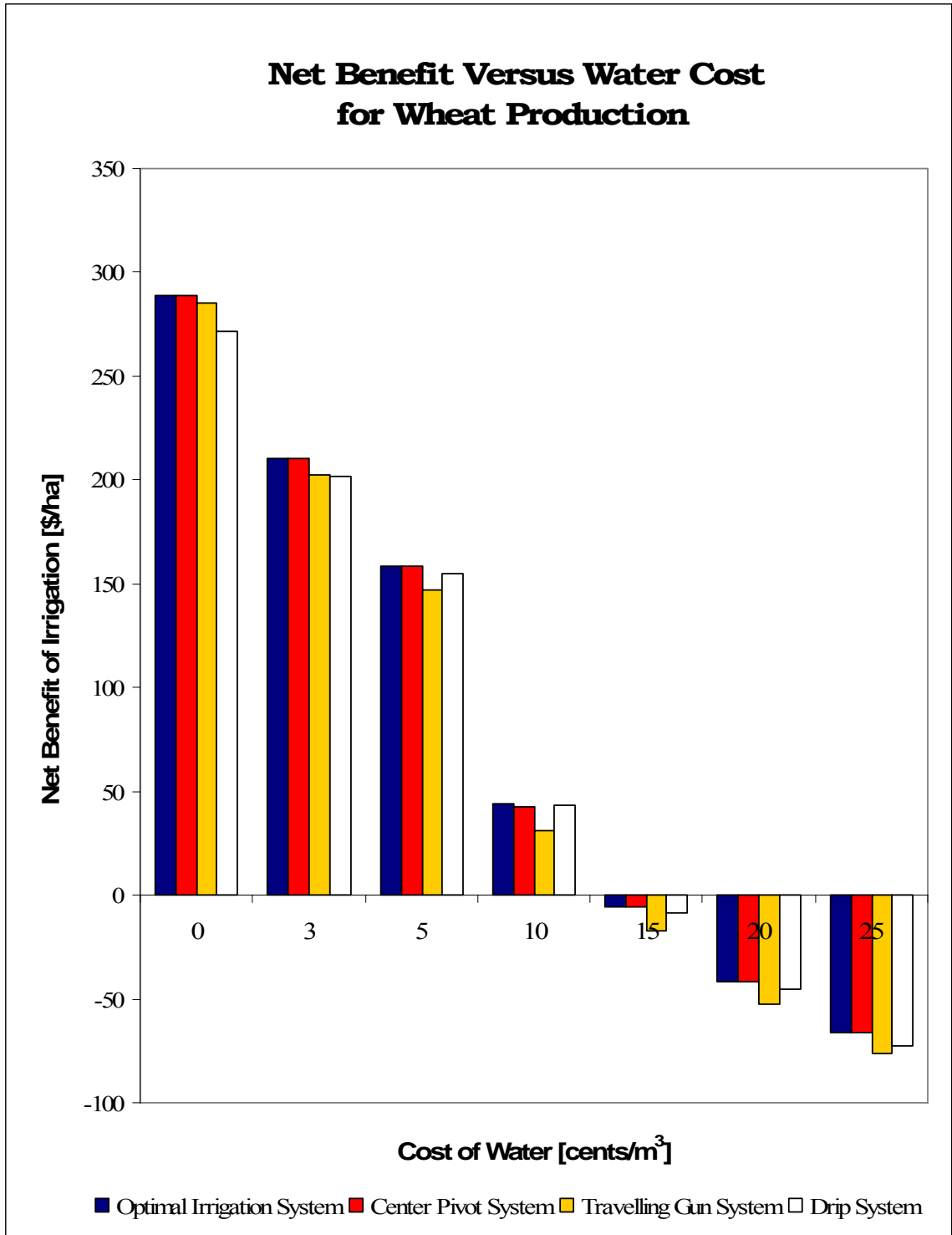
In the case of soybean and wheat the relationship between net benefit and the cost of water follows the same general trend for that of corn production for each of the three irrigation systems compared. In each case, the net benefit of irrigation decreases with the increasing water cost level until finally crop production is no longer profitable with the economic burden of irrigation installations.

In the case of soybean production (Figure 25), irrigation remains marginally profitable up to a water cost level of 20 cents/m<sup>3</sup>; while wheat production (Figure 26)

becomes unprofitable above a water cost level of 10 cents/m<sup>3</sup>. This difference is predominately due to the fact that soybean is the more valuable crop (\$265 /metric ton for soybeans compared to \$115 /metric ton for wheat), and therefore has a greater net return for crop yield increases resulting from applied water.



**Figure 25.** Irrigation system comparison of net benefit versus water cost associated with soybean production.



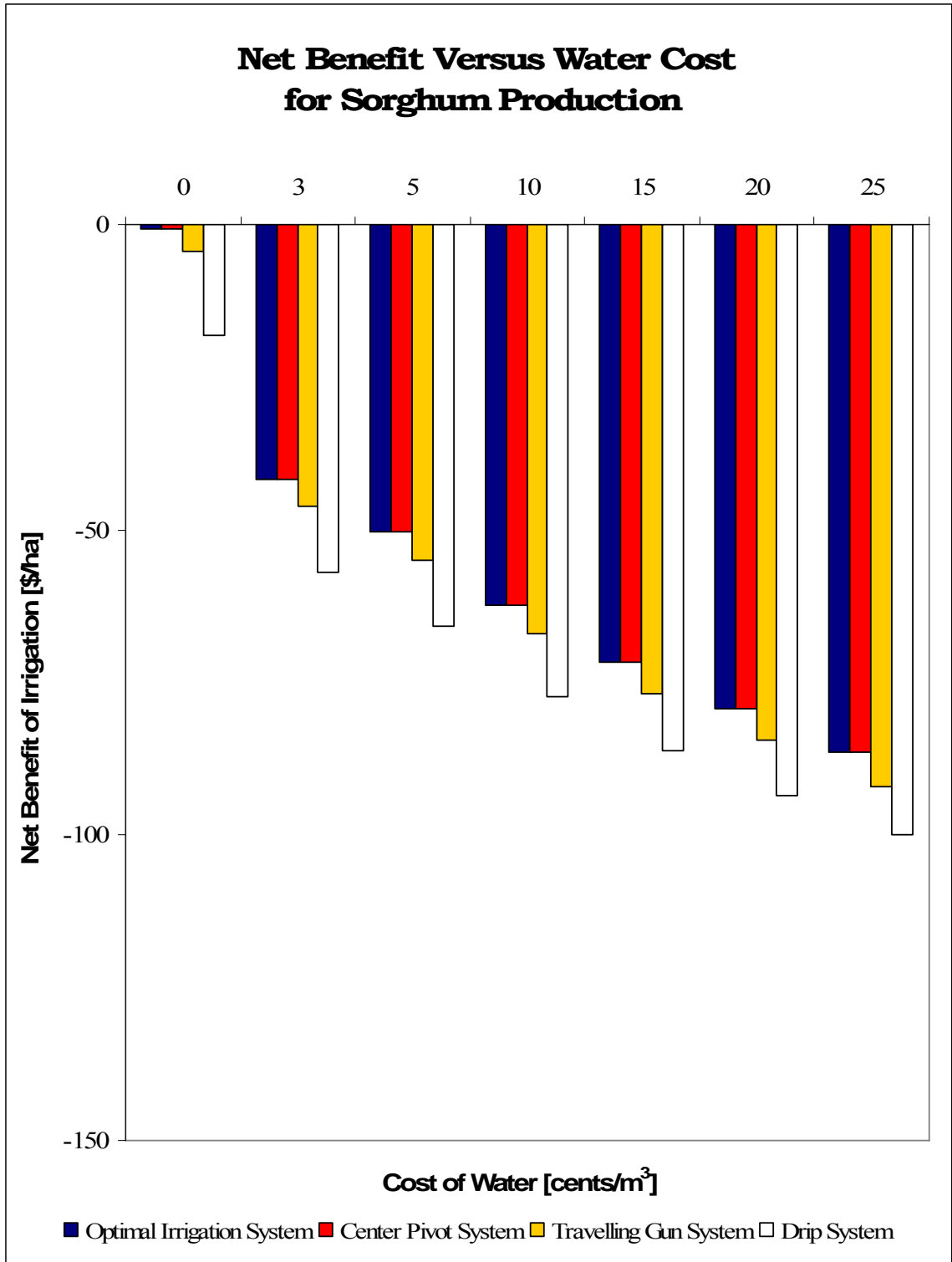
**Figure 26.** Irrigation system comparison of net benefit versus water cost associated with wheat production.

As in the case of corn production, center pivot irrigation emerges as the most profitable of the three systems at water cost levels less than 5 cents/m<sup>3</sup>; while drip irrigation becomes increasingly more competitive as the cost of water increases. In the case of sorghum production (Figure 27), the net benefit of each system is negative in all cases. The net benefit values associated with drip irrigation remain significantly below that of both the center pivot system and traveling gun system. However, as the water cost level increases the gap between them narrows.

Sorghum is the least expensive of the crops compared in this analysis and the least productive in terms of yield per hectare<sup>27</sup>. As a result the annual irrigation installation and maintenance expense is too great a burden for the modest revenue generated through sorghum production. Given the economic data used in this study, sorghum production, in combination with the added cost of the irrigation system, remains unprofitable even when the price of water is zero cents/m<sup>3</sup>, at which point the irrigation system is at its maximum beneficial use. As the cost of water increases the beneficial use of the irrigation system decreases, until finally there is no beneficial use to the irrigation system, and the irrigation system becomes entirely a burden to production resulting in no increase in yield. The result is a greater net deficit income as shown in the Figure 27; and irrigation remains unprofitable for all water cost levels for each system compared.

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<sup>27</sup> As determined by the Maryland Agricultural Statistics Service (MASS, 2004) in statewide statistical data presented previously.



**Figure 27.** Irrigation system comparison of net benefit versus water cost associated with sorghum production.

Figures 24 through 27 present the average net benefit values at each water cost level associated with irrigation, but do not include a comparison of the net benefit of agricultural production without irrigation. The estimated net benefit of agricultural production without irrigation for each crop is presented in Tables 15 through 17. Table 18 presents the percentage of agricultural land in which the net benefit with irrigation is greater than the net benefit of production without irrigation. These values are determined by summing the area of each HRU in which the net benefit with irrigation is greater than the net benefit without irrigation, and dividing by the total area of all agricultural fields (agricultural HRU's) within the area of interest. The percentage of land resulting in greater profit with irrigation is calculated at each water cost level and is presented in Table 18.

**Table 18.** Percentage of agricultural land associated with a higher net benefit value with irrigation than without irrigation, at each water cost level.

<b>Crop</b>	<b>Percentage of Land at a Water Cost = 0 cents/m<sup>3</sup></b>	<b>Percentage of Land at a Water Cost = 3 cents/m<sup>3</sup></b>	<b>Percentage of Land at a Water Cost = 5 cents/m<sup>3</sup></b>	<b>Percentage of Land at a Water Cost = 10 cents/m<sup>3</sup></b>
Corn	84.99	70.83	20.72	0.00
Soybean	87.53	75.59	23.06	0.00
Wheat	84.99	53.60	21.40	0.00
Sorghum	0.00	0.00	0.00	0.00

At a water cost level of 0 cents/m<sup>3</sup> over 80% of the agricultural land within the Pocomoke watershed, in which corn, soybean or wheat is produced, had a greater net benefit with irrigation than without. This percentage rapidly decreased to just over 20% at a water cost level of 5 cents/m<sup>3</sup> for corn, soybean and wheat. At higher water cost levels (10 cents/m<sup>3</sup> and above) no agricultural fields were found with a greater net benefit

with irrigation than without. Irrigation was not found to be profitable with sorghum at any water cost level and for any HRU.

These comparisons evaluate each crop on an individual basis, however, in order to determine if irrigation results in greater profit overall, consideration will have to be given to the crop rotation appropriate for each location. The weighted average net benefit with irrigation will need to be determined by averaging the net benefit values for each individual crop included in the crop rotation. This value can then be compared to the estimated net benefit of agricultural production without irrigation based on the same crop rotation.

In summary, optimal irrigation system selection is found to depend heavily upon the price of water and the installation and maintenance costs of the system. Initially, it was expected that irrigation system selection may depend, to a more significant degree, on the physical characteristics of the terrain and the associated properties of the HRU. It was expected that this sort of modeling could more clearly delineate between HRUs that favor more water efficient systems and those HRUs that profit more from less expensive but less conservative systems. Such diversification of irrigation system recommendations did occur to a limited degree, however, it was overshadowed by the prevailing influence of the cost of water and irrigation installation costs. Nevertheless, model recommendation variation did occur, with the *IrrigEcon* application recommending the most economically favorable system based upon the physical characteristics of widely different HRUs, given the same set of initial economic conditions.

However, overall, HRU parameter variations did not substantially influence the determination of the most economic irrigation system. Instead, at the lower water cost



level the center pivot system, characterized by moderate installation costs, low maintenance, and moderate water use efficiency, was found to be most economical, yielding the highest net benefit under nearly all applicable HRU conditions.

As cost of water increased, during successive simulations, drip irrigation, characterized by higher installation and maintenance costs but higher water use efficiency, was increasingly recommended as the most economically beneficial system due to its added savings achieved through water conservation. Under the simulation and economic conditions defined in this project, the traveling gun irrigation system, characterized by low installation costs, higher maintenance and low irrigation distribution efficiency was found to be the least economical of all systems. However, an overall trend was observed in which traveling gun systems became more economically favorable as the cost of water decreased, although the associated net benefit remained beneath that of center pivot systems at all times. It is clear that had lower installation or maintenance costs been associated with the traveling gun system, it will be increasingly prevalent at lower water cost levels.

### **Statistical Analysis of Irrigation Economics:**

Based on the graphical information presented in the previous sections, the unit cost of water and the water distribution efficiency associated with each irrigation system, appear to be the most pertinent irrigation selection criterion for determining the most economically favorable irrigation system. The pages that follow present the results of the statistical analysis used in determining and contrasting the divergent model considerations and physical parameters that influence the selection of the recommended irrigation system for a given water cost level.

The analysis revolves around determining which physical parameters, associated with the various soil types and HRU characteristics, are most influential in contributing to the recommendation of one irrigation system over another at a given water cost level. For instance, for mid-range water cost levels varying between 5 and 20 cents per cubic meter, the center pivot system is recommended for certain HRUs, while the drip irrigation system is recommended for other HRUs within the same watershed. Therefore, for a given crop and at a set irrigation water cost level, it is clear that there are additional pertinent parameters that influence the selection of the various irrigation systems considered.

The goal of the statistical analysis is to determine those variables, which differ between the HRUs, that cause the more expensive, more efficient, drip irrigation system to result in the greatest economic advantage; and those variables that result in circumstances where the less efficient but less expensive center pivot system is recommended. For each of these HRUs the economic data applied is identical in that the same crop is grown, receiving the same price per unit yield, and the identical economic costs are applied on a per hectare basis in terms of the irrigation maintenance and installation costs, and crop production costs.

Despite the identical economic values applied, the model may or may not recommend irrigation application for individual HRUs, and, in those cases where irrigation is recommended, may select different irrigation systems for distinct HRUs based on the value of specific physical parameters associated with each of these HRUs. These differences in irrigation system recommendations can only be attributed to the

varying characteristics associated with each HRU. The specific goal of this section is to identify those variables that exert the greatest influence on irrigation selection.

The analysis is conducted both laterally, considering various crops produced in Maryland for which appropriate  $k_y$  values are available, and in-depth, by determining the factors that influence the preference of one irrigation system over another given the same production and associated economic factors. Further analysis contrasts the physical parameters of the various HRU's that influence the net benefit of irrigation for a given crop. The data included in this analysis is a composite of: the .sbs output information obtained from SWAT output files for each HRU; the STATSGO soil data for each soil type within the watershed and attributed to individual HRUs; the topography and elevation data for each subbasin; and the irrigation system recommendation data obtained as an output of the *IrrigEcon* model.

*Primary Factors in Determining Irrigation Application:*

Using the SAS 'MIXED' ANOVA analysis several factors emerge that are found to influence whether or not irrigation system installation and water application is recommended. Table 19 includes a selected list of variables considered in the ANOVA analysis and the calculated  $f$ -value and associated probability. The table distinguishes between economic variables, SWAT variables including parameters associated with the HRU and the crop physical characteristics, and variables associated with the soil type. The ANOVA analysis indicates that mean value associated with each parameter listed in Table 19 is significantly different, within a probability of 99%, when irrigation is recommended and when irrigation is not recommended.

A full listing of ANOVA probability values for SWAT variables, included in the statistical analysis but not included in the table below, is presented in Appendix G of this report. These variables were not include in the table below as they relate to hydrologic and nutrient concentration parameters strongly correlated to parameters already included in the Table 19.

**Table 19.** Results of the analysis of variance (ANOVA) in determining the factors that influence model recommendations for the application or non-application of irrigation.

<b>Model Variable</b>	<b>Variable Description</b>	<b>Num. DF</b>	<b>Den. DF</b>	<b>F-Value</b>	<b>Associated Probability</b>
<b><i>Economic Parameters:</i></b>					
WaterCost	Cost of water per unit volume	1	8671	2446.62	<0.0001
Ky	Crop response factor	1	8671	28.19	<0.0001
IrrInsCost	Irrigation Installation Costs	1	8671	949.17	<0.0001
IrrigEff	Irrigation Distribution Efficiency	1	8671	949.17	<0.0001
<b><i>.SBS SWAT Parameters</i></b>					
SUB	Topographically defined subbasin	78	8594	1.80	<0.0001
HRU	Hydrologic response unit	1	8671	21.45	<0.0001
LULC	Crop Type -Land cover/plant associated with HRU	6	8666	947.65	<0.0001
YLD	Yield quantity without irrigation application	1	6547	48.00	<0.0001
MEANEL	Average mean elevation of subbasin	1	8671	9.54	0.0020
MINELEV	Average minimum elevation of subbasin	1	8671	6.51	0.0107
MAXELEV	Average maximum elevation of subbasin	1	8671	8.43	0.0037
PRECIP	Precipitation falling on HRU	1	6547	32.03	<0.0001
PET	Potential evapotranspiration	1	6547	20.89	<0.0001
ET	Actual evapotranspiration	1	6547	251.16	<0.0001
WSTRS	Water stress days	1	6547	999.87	<0.0001
TMPSTRS	Temperature stress days	1	6547	88.45	<0.0001
<b><i>Soil Parameters:</i></b>					
SoilType	Soil type	11	8661	12.40	<0.0001
Ldepth	Top soil layer depth	1	8671	25.80	<0.0001
AWC	Available water capacity of the soil layer	1	8671	34.86	<0.0001
HydCond	Hydraulic conductivity of top soil layer	1	8671	10.80	0.0010
pClay	Percent clay content of top soil layer	1	8671	101.49	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	29.65	<0.0001
pSand	Percent sand content of top soil layer	1	8671	43.81	<0.0001

Table 20 lists the mean value and the standard error for parameters influential in determining irrigation recommendations. Subbasin, land use and soil type values are all

factors that influence the determination of irrigation recommendation; however as these are categorical variables that do not have an associated mean value and therefore are not included in Table 20. Instead descriptive factors such as the mean, min/max elevation of the subbasin, yield quantity (without irrigation) and price, as well as additional soil layer data are included.

**Table 20.** Mean and standard error values for relevant economic, subbasin and soil parameters associated with irrigation recommendation

Model Variable	Variable Description	Irrigation Recommended		Irrigation Not Recommended	
		Mean Value	Standard Error	Mean Value	Standard Error
<b><i>Economic Parameters:</i></b>					
WaterCost	Cost of water [\$/m <sup>3</sup> ]	0.0846	0.000978	0.1716	0.001464
Ky	Crop response factor	0.8952	0.002238	0.8738	0.003350
IrrInsCost	Irrigation Installation Costs	83050	106.41	88950	159.25
IrrigEff	Irrigation Distribution Efficiency	0.9040	0.000608	0.8703	0.00091
<b><i>.SBS SWAT Parameters</i></b>					
YLD	Yield quantity without irrigation application [ton/ha]	1.7970	0.02395	1.5082	0.03410
MEANEL	Average mean elevation of subbasin [cm]	946.87	4.2118	923.46	6.3034
MINELEV	Average minimum elevation of subbasin [cm]	394.38	4.4716	373.84	6.6922
MAXELEV	Average maximum elevation of subbasin [cm]	1495.84	5.6053	1466.55	8.3889
PRECIP	Precipitation falling on HRU [mm]	1084.70	0.1547	1083.18	0.2203
PET	Potential evapotranspiration [mm]	1263.88	0.09932	1263.09	0.1414
ET	Actual evapotranspiration [mm]	492.35	0.6238	475.15	0.8883
WSTRS	Water stress days	50.9329	0.4178	27.9474	0.5949
TMPSTRS	Temperature stress days	41.2460	0.6291	30.9506	0.8959
<b><i>Soil Parameters:</i></b>					
Ldepth	Top soil layer depth [mm]	253.20	0.4558	249.03	0.6822
AWC	Available water capacity of the soil layer [mm water/mm soil]	0.1521	0.000526	0.1577	0.000786
HydCond	Hydraulic conductivity of top soil layer [mm/hr]	91.8478	1.2006	84.7447	1.7969
pClay	Percent clay content of top soil layer [%]	12.1147	0.05017	13.0245	0.07509
pSilt	Percent silt content of top soil layer [%]	34.9379	0.2427	37.3169	0.3633
pSand	Percent sand content of top soil layer [%]	52.9474	0.2760	49.6587	0.4131
Ldepth2	Soil layer depth of second soil layer [mm]	846.60	4.3238	816.36	6.4710
AWC2	Available water capacity of the second soil layer [mm water/mm soil]	0.1251	0.000530	0.1341	0.000793
HydCond2	Hydraulic conductivity of	69.8963	0.8806	62.9766	1.3179

Model Variable	Variable Description	Irrigation Recommended		Irrigation Not Recommended	
		Mean Value	Standard Error	Mean Value	Standard Error
	second soil layer [mm/hr]				
pClay2	Percent clay content of second soil layer [%]	16.0219	0.1048	17.3145	0.1569
pSilt2	Percent silt content of second soil layer [%]	26.2639	0.2079	30.1891	0.3112
pSand2	Percent sand content of second soil layer [%]	57.7142	0.2909	52.4964	0.4353

Of the factors listed in Table 20, an obvious factor in determining if irrigation is, or is not, recommended is the cost of water and the cost of the irrigation system. Both variables are calculated in the ANOVA analysis with an associated probability of less than 0.0001, although the cost of water is associated with an  $f$ -value of nearly 2450, while the cost of the irrigation system is associated with an  $f$ -value of nearly 950. These values are extremely decisive, given the large number of samples, however, the larger  $f$ -value associated with the cost of water may imply that the cost of the water is the more dominant variable in determining if irrigation is recommended.

This may be apparent if it is considered that the *IrrigEcon* model is programmed to recommend irrigation application based on the expected net benefit, and therefore the cost of irrigation water application is a primary factor in the decision making process. This is apparent from the plot of recommended irrigation volume versus the cost of water presented in the previous section. Low water cost levels ( $\leq 10$  cents/m<sup>3</sup>) lead to significant and widespread water application for the majority of crop types, while higher water costs levels ( $> 10$  cents/m<sup>3</sup>) lead to reduced water application recommendations.

In line with the cost of irrigation application is the crop water demand as reflected in both the number of water stress days for a given year, and the actual and potential



evapotranspiration values associated with a given simulation year. The factors that influence water stress, given an identical applied weather pattern, are the plant physiology, soil properties and the crops' tolerance to drought conditions as represented by its  $k_y$  value.

It is observed that the number of water stress days associated simulations in which irrigation is recommended is nearly double the number of water stress days associated with simulations in which irrigation is not recommended. In addition, both the mean actual evapotranspiration rate and the number of temperature stress days associated with simulations where irrigation is recommended are significantly higher than those simulations in which irrigation is not recommended. The variation in climatic factors was evenly applied; however, the effect in terms of actual evapotranspiration and temperature stress is determined by crop response and physical characteristics which vary with each crop species.

Simulations involving specific crops are recommended for irrigation based on crop response and economic variables associated with the crop. Table 20 shows that crops with higher average yields per hectare, associated with higher crop prices and a higher crop response factor ( $k_y$ ), are more likely to be selected for irrigation application. Higher crop response factors indicate that an increase in the ratio of actual to potential evapotranspiration, as would be expected as a result of applied irrigation, will result in a more rapid increase in the ratio of actual yield to potential yield. From the simulations conducted, 95.0 % of fields involving corn production, 83.4 % of fields involving soybean production, 63.4 % of fields involving wheat production, and 6.1 % of fields involving sorghum production were recommended for irrigation application.

Surprisingly, the difference between the mean annual precipitation and the potential evapotranspiration values for simulations where irrigation is and is not recommended was only 1-2 mm of water. This slight difference, although indicated in the ANOVA analysis as statistically different, is comparatively insignificant. Instead factors associated with the subbasin, the crop type and soil type appear to have a more direct impact on irrigation recommendations.

The statistical data presented in Table 20 shows that irrigation is recommendation more often for subbasins associated with higher elevations when compared to low land areas associated with lower elevations. In addition, irrigation recommendation is greater with fields associated with higher sand content and lower clay and silt contents. Soils associated with higher sand content are also associated with higher hydraulic conductivity values and are therefore more easily drained. Well drained soils, while favorable to certain crop species, run a greater risk of extended periods of water stress, between precipitation events, than do soils with higher clay and silt content and higher average available water content.

In order to present this information spatially, each HRU is assessed a score based on the frequency in which irrigation is recommended by the *IrrigEcon* application. For each simulation and at all water cost levels the HRU is assigned an irrigation recommendation value of either 1 or 0 (referred to as a *Rating Value*), based on whether irrigation is or is not recommended. This value is then normalized based on the size of the HRU by multiplying the rating value by the area of the HRU and dividing by the area of all agricultural HRUs within the associated subbasin.

A score is then assigned to each subbasin as the sum of all HRU scores within the subbasin. Equations 28 and 29 show a generalized calculation for determining the HRU and subbasin score.

$$HRU\_Score = RatingValue \times \frac{HRU\_Area}{\sum SubHRU\_Area} \quad (28)$$

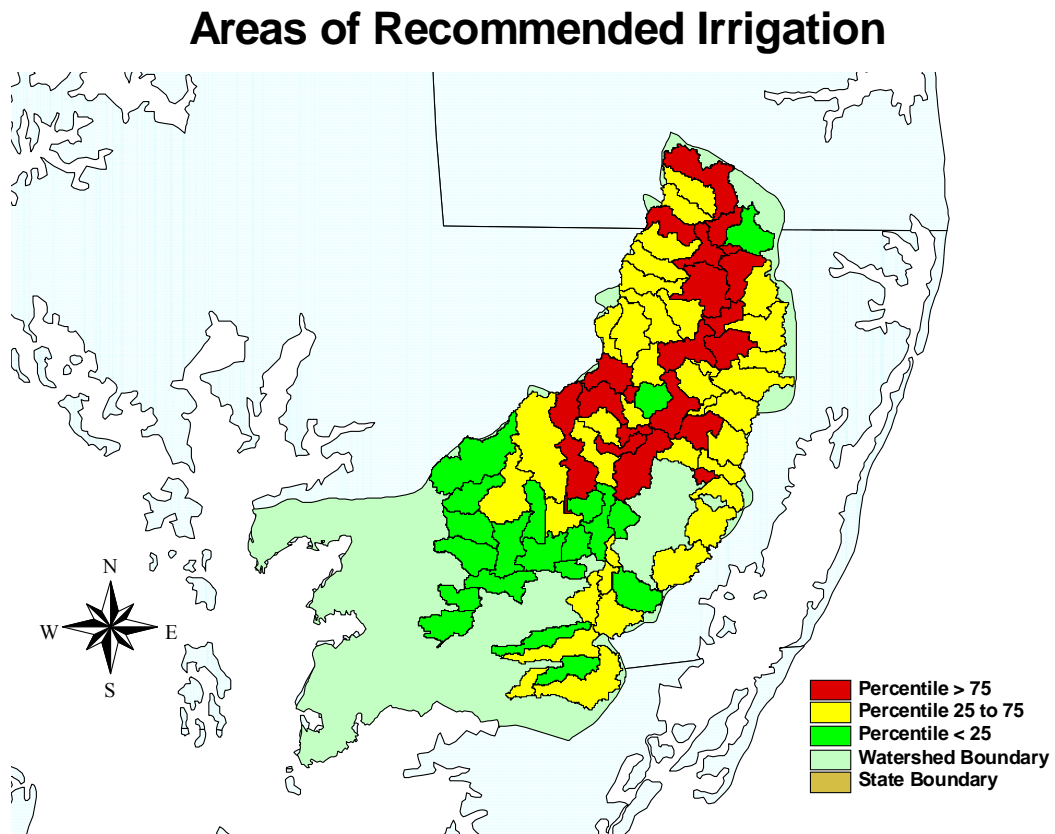
$$SUB\_Score = \sum HRU\_Score \quad (29)$$

Where the *RatingValue* is the value applied to each HRU sample in order to differentiate between irrigated and non irrigated HRUs, the *HRU\_Area* is the total area of the HRU [ha], the *SubHRU\_Area* is the area of all agricultural HRUs within the subbasin [ha], and the *HRU\_Score* and *SUB\_Score* are the scores received by the HRU and subbasin, respectively.

The subbasins with the highest scores are associated with agricultural fields where irrigation is most frequently prescribed based upon the *IrrigEcon* application calculations, as influenced by the factors discussed above. This information is then spatially presented in Figure 28.

The subbasins are categorized based on the score received as either above average, average or below average for the frequency of irrigation recommendation. Subbasins with scores falling within the 75<sup>th</sup> percentile or greater are categorized as above average, while subbasins with scores falling between the 25<sup>th</sup> and 75<sup>th</sup> percentile are considered average, and subbasins with scores falling below the 25 percentile mark

are considered below average. Figure 28 presents this information in a GIS layout of the areas of interest incorporated into the original SWAT model.



**Figure 28.** Spatial delineation of subbasin irrigation recommendation based on applied rating system.

*Primary Factors in Determining Irrigation System Selection:*

The analysis discussed above differentiates between simulations in which irrigation is and is not recommended. The same analysis of variance procedure is applied to the model data in order to differentiate between irrigation system selections. The

ANOVA procedure uses the recommended irrigation system associated with the greatest net benefit as the dependent variable.

The intent of this analysis is to determine the predominant factors that determine which irrigation system will emerge as the optimal system for a given set of conditions. This analysis looks solely at those instances in which irrigation is recommended, and compares and contrasts relevant factors that are associated with simulations in which any of the three irrigation systems is recommended. In contrast, the preceding section compared and contrasted simulations where irrigation installation (independent of the type of system) is or is not recommended.

Table 21 includes the calculated  $f$ -values and the associated probability for the ANOVA analysis. As in the case above regarding irrigation recommendation, a probability of 99 % or greater is considered to be statistically significant. Table 22 that follows includes the mean value of each parameter and the associated standard error for simulations in which either the center pivot irrigation system is found to be the optimal system in terms of maximum net benefit, or those simulations in which drip irrigation was found to be the optimal system. Given the economic data used in the *IrrigEcon* model, the traveling gun system was not found to be the most economical system in any simulation, and therefore no mean data is available for simulations involving this system.

**Table 21.** Results of the analysis of variance (ANOVA) in determining the factors that influence the model irrigation system selection

<b>Model Variable</b>	<b>Variable Description</b>	<b>Num. DF</b>	<b>Den. DF</b>	<b>F-Value</b>	<b>Associated Probability</b>
<b><i>Economic Parameters:</i></b>					
WaterCost	Cost of water per unit volume	1	8671	1333.00	<0.0001
Ky	Crop response factor	1	8671	0.48	0.4881
<b><i>.SBS SWAT Parameters</i></b>					
SUB	Topographically defined subbasin	78	8594	3.04	<0.0001
HRU	Hydrologic response unit	1	8671	29.38	<0.0001
LULC	Crop Type -Land cover/plant associated with HRU	6	8666	486.50	<0.0001
YLD	Yield quantity without irrigation application	1	6547	230.78	<0.0001
MEANEL	Average mean elevation of subbasin	1	8671	13.79	0.0002
MINELEV	Average minimum elevation of subbasin	1	8671	7.08	0.0078
MAXELEV	Average maximum elevation of subbasin	1	8671	14.13	0.0002
PRECIP	Precipitation falling on HRU	1	6547	20.15	<0.0001
PET	Potential evapotranspiration	1	6547	0.76	0.3843
ET	Actual evapotranspiration	1	6547	46.95	<0.0001
WSTRS	Water stress days	1	6547	581.77	<0.0001
TMPSTRS	Temperature stress days	1	6547	94.31	<0.0001
<b><i>Soil Parameters:</i></b>					
SoilType	Soil type	11	8661	23.08	<0.0001
Ldepth	Top soil layer depth	1	8671	35.23	<0.0001
AWC	Available water capacity of the soil layer	1	8671	95.98	<0.0001
HydCond	Hydraulic conductivity of top soil layer	1	8671	29.73	<0.0001
pClay	Percent clay content of top soil layer	1	8671	194.86	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	71.47	<0.0001
pSand	Percent sand content of top soil layer	1	8671	99.43	<0.0001

As with the case of irrigation recommendation, the cost of water, crop type and the water stress days all emerge as the most dominant factors that determine which irrigation system is to be recommended as the most optimal system. Dominance in this case is determined by the relative magnitude of the  $f$ -value as opposed to the magnitude

of the associated probability. However, unlike in the analysis of the irrigation application data, the crop response factor ( $k_y$ ) did not emerge as a relevant factor in determining irrigation system selection.

The crop response factor is a function of the crop type, which is found to be significantly different between recommended irrigation systems, however, the importance of the crop response factor is more heavily connected to the crop's physiological response to water deficit as indicated by the statistical significance of the quantity of stress days, and economic factors associated with the crop such as yield and crop price.

Overall the cost of water appears to be the most significant factor in determining the type of system that is recommended, as indicated by the magnitude of the  $f$ -value. The three irrigation systems considered are associated with various efficiency values, and therefore require different volumes of water for the same net effect. As a result the cost of water remains an obvious factor in determining irrigation system selection.

The water stress intensity of the crop is seen to be strongly statistically significant. The water stress intensity is closely correlated with the water demand, and becomes a more relevant factor in determining the recommended irrigation system as the water cost level rises. At lower water cost levels (10 cents per cubic meter or less) the water demand is easily met by all irrigation systems with little effect on the overall net benefit; as water costs rise the distribution efficiency of the irrigation system becomes a more dominant factor in the irrigation system selection process.

**Table 22.** Mean and standard error values for relevant economic, subbasin and soil parameters associated with the selected optimal irrigation system

Model Variable	Variable Description	Center Pivot Irrigation System		Drip Irrigation System	
		Mean Value	Standard Error	Mean Value	Standard Error
<i>Economic Parameters:</i>					
WaterCost	Cost of water [\$/m <sup>3</sup> ]	0.08391	0.001142	0.1470	0.001299
Ky	Crop response factor	0.8897	0.002482	0.8871	0.002823
<i>.SBS SWAT Parameters</i>					
YLD	Yield quantity without irrigation application [ton/ha]	1.4954	0.02362	2.1198	0.03364
MEANEL	Average mean elevation of subbasin [cm]	928.21	4.6617	954.43	5.3026
MINELEV	Average minimum elevation of subbasin [cm]	379.35	4.9503	399.29	5.6309
MAXELEV	Average maximum elevation of subbasin [cm]	1471.41	6.2036	1506.7	7.0564
PRECIP	Precipitation falling on HRU [mm]	1083.80	0.1548	1085.0	0.2205
PET	Potential evapotranspiration [mm]	1263.57	0.09948	1263.7	0.1417
ET	Actual evapotranspiration [mm]	484.17	0.6334	491.72	0.9019
WSTRS	Water stress days	37.3830	0.4298	55.423	0.6121
TMPSTRS	Temperature stress days	34.3360	0.6288	44.962	0.8955
<i>Soil Parameters:</i>					
Ldepth	Top soil layer depth [mm]	249.94	0.5043	254.47	0.5737
AWC	Available water capacity of the soil layer [mm water/mm soil]	0.1576	0.000580	0.1490	0.000659
HydCond	Hydraulic conductivity of top soil layer [mm/hr]	84.8754	1.3278	95.839	1.5103
pClay	Percent clay content of top soil layer [%]	12.9047	0.05525	11.736	0.06285
pSilt	Percent silt content of top soil layer [%]	37.1686	0.2681	33.736	0.3049
pSand	Percent sand content of top soil layer [%]	49.9266	0.3046	54.527	0.3465
Ldepth2	Soil layer depth of second soil layer [mm]	820.90	4.7836	858.44	5.4412
AWC2	Available water capacity of the second soil layer [mm water/mm soil]	0.1329	0.000584	0.1213	0.000664
HydCond2	Hydraulic conductivity of second soil layer [mm/hr]	63.5700	0.9736	73.182	1.1074



Model Variable	Variable Description	Center Pivot Irrigation System		Drip Irrigation System	
		Mean Value	Standard Error	Mean Value	Standard Error
pClay2	Percent clay content of second soil layer [%]	17.0648	0.1159	15.587	0.1318
pSilt2	Percent silt content of second soil layer [%]	29.5657	0.2291	24.770	0.2606
pSand2	Percent sand content of second soil layer [%]	53.3695	0.3208	59.641	0.3649

When comparing the mean value of many of the significant factors that influence the selection of one system over another, it is apparent that similar trends exist between simulations in which drip irrigation is selected over center pivot irrigation, and simulations in which irrigation application is recommended over simulation in which irrigation application is not recommended. This similarity is apparent when recalling that drip irrigation is generally favored at higher water cost levels and in simulations where irrigation is more valued. At lower water cost levels it is observed that center pivot irrigation is favored due to its lower monthly cost as a result of lower installation and maintenance cost associated with the system. However, as water cost becomes a more significant factor, drip irrigation is favored in cases where irrigation is more valued. Simulation conditions in which drip irrigation is associated with the greatest net benefit generally represent the more extreme cases where irrigation is most needed; the general characteristics of these simulations are reflected in the mean values presented in Table 22.

As is the case with irrigation application, drip irrigation is favored for crops associated with higher yields, higher actual evapotranspiration rates, and greater water and temperature stress days; as well as with HRUs generally associated with higher hydraulic conductivity values, higher sand content with lower silt and clay content, lower

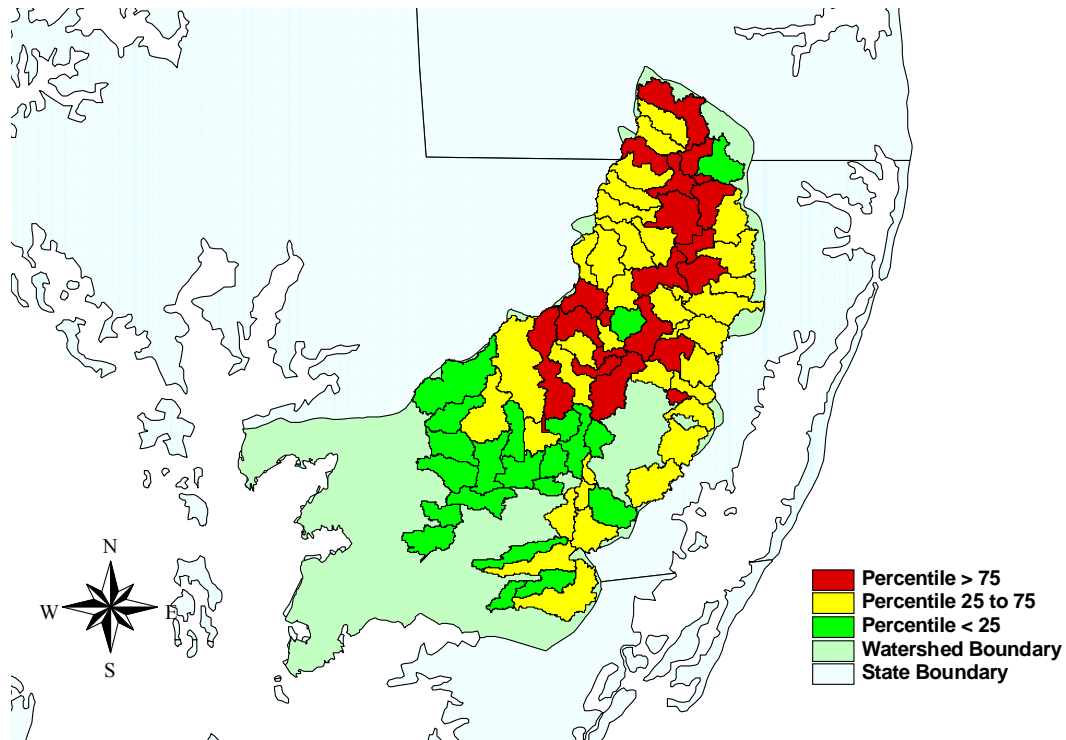
available water content values, and generally associated with subbasins located at higher elevations. These traits have been shown to be associated with simulations in which drip irrigation is favored due to its higher efficiency value, and more effective application at higher water cost levels.

Irrigation selection information is presented spatially by means of a rating system for each subbasin within the area of interest. The distribution of subbasins that favor drip irrigation versus center pivot irrigation varies with each water cost level. Therefore, a rating system is applied to all subbasins in order to differentiate between subbasins that, overall, favor the more efficient drip irrigation system versus the less efficient center pivot system.

Similar to the case of the irrigation recommendation rating system the model data was compiled and each HRU, at all water cost levels for which irrigation is recommended, is assigned a rating value of 1, 2 or 3. The value assigned corresponds to the irrigation system marked as the optimal system for each HRU. The highest value, a value of 3, is associated with the HRUs in which the optimal system is the more efficient drip irrigation system; a value of 2 is associated with HRUs in which the center pivot system is the optimal irrigation system; and a value of 1 is assigned to HRUs associated with the less efficient traveling gun system (in the case of this study, no HRU was assigned a value of 1 as the traveling gun system was not found to be the optimal system for any area given the simulations conducted). The values are then normalized by multiplying the value by the area of the HRU and dividing by the total area of all HRUs within the associated subbasin. The overall score assigned to each subbasin is the sum of the scores for all HRUs located within the subbasin.

The subbasins ranked with the highest scores are associated with those areas that favor the more efficient drip irrigation system; lower scores are associated with areas that favor the less expensive and less efficient center pivot system. As with the case of the irrigation recommendation rating system, the subbasins are then group based on the percentile of the subbasin score and presented in the Figure 29. Subbasins that are ranked within the 75<sup>th</sup> percentile or greater represent areas in which drip irrigation is recommended as the optimal system more frequently; while subbasins that are ranked in the 25<sup>th</sup> percentile or less are those subbasins that favor the less efficient center pivot system; subbasins with intermediate scores are of mixed application.

## Areas that Favor Drip Irrigation



**Figure 29.** Spatial delineation of subbasins favoring drip irrigation based upon applied rating system.

### *Primary Factors Influencing the Predicted Net Benefit:*

Using the maximum net benefit as the dependent variable, in the ANOVA test, results in the determination of a wide range of variables that are statistically significant in affecting the annual net benefit of irrigation. These variables include economic values, crop type, and factors associated with the soil type and properties of the particular HRU.

Some of the most significant of these factors include the economic variables that determine overall production costs and revenue generated, such as the cost of water, crop

yield and the price received by the farmer for each crop. Factors such as water cost, crop type and yield affect the economic variables associated with the net benefit of the system, while factors such as the degree of water and temperature stress associated with the crop without irrigation affect the resulting yield produced. Crop stresses experienced by the plant, such as stress caused by water deficit or extremes of temperature stress, affect plant growth and subsequently the productivity of the system, thereby having a direct impact on the overall net benefit of the system. Table 23 presents the results of the ANOVA test on the net benefit of the system. The table includes the calculated *f*-value and the associated probability of each of the factors analyzed.

**Table 23.** Results of the analysis of variance (ANOVA) in determining the factors that influence annual net benefit values.

<b>Model Variable</b>	<b>Variable Description</b>	<b>Num. DF</b>	<b>Den. DF</b>	<b>F-Value</b>	<b>Associated Probability</b>
<b><i>Economic Parameters:</i></b>					
WaterCost	Cost of water per unit volume	1	8671	5122.72	<0.0001
Ky	Crop response factor	1	8671	6.78	0.0092
IrrInsCost	Irrigation Installation Costs	1	8671	17.10	<0.0001
IrrigEff	Irrigation Distribution Efficiency	1	8671	17.10	<0.0001
<b><i>.SBS SWAT Parameters</i></b>					
SUB	Topographically defined subbasin	78	8594	2.23	<0.0001
HRU	Hydrologic response unit	1	8671	43.77	<0.0001
LULC	Crop Type –Land cover/plant associated with HRU	6	8666	1239.87	<0.0001
YLD	Yield quantity without irrigation application	1	6547	114.31	<0.0001
MEANEL	Average mean elevation of subbasin	1	8671	23.54	<0.0001
MINELEV	Average minimum elevation of subbasin	1	8671	19.74	<0.0001
MAXELEV	Average maximum elevation of subbasin	1	8671	20.67	<0.0001
PRECIP	Precipitation falling on HRU	1	6547	47.25	<0.0001
ET	Actual evapotranspiration	1	6547	471.34	<0.0001
WSTRS	Water stress days	1	6547	3276.03	<0.0001
TMPSTRS	Temperature stress days	1	6547	1300.60	<0.0001
<b><i>Soil Parameters:</i></b>					
SoilType	Soil type	11	8661	13.37	<0.0001
Ldepth	Top soil layer depth	1	8671	53.61	<0.0001
AWC	Available water capacity of the soil layer	1	8671	16.81	<0.0001
HydCond	Hydraulic conductivity of top soil layer	1	8671	9.08	0.0026
pClay	Percent clay content of top soil layer	1	8671	103.49	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	13.26	0.0003
pSand	Percent sand content of top soil layer	1	8671	25.49	<0.0001

In the previous analysis, the factors that influence irrigation application or irrigation system selection are first identified by the results of the ANOVA test, followed by the direct comparison of the mean value of each variable for each category (irrigation

application or irrigation system selection). However, in the case of the net benefit analysis, distinct categories are not applicable and therefore, a regression analysis is preformed, which determines the best fit linear function of the net benefit verses the independent variable being considered. This allows for the determination of the relative affect each parameter has on the predicted maximum net benefit. Table 24 presents the results of the regression analysis, which includes the adjusted R-squared value, the dependent axis intercept ( $y$ -intercept) and the slope associated with the linear regression function, as well as the standard error associated with both the  $y$ -intercept and the function's slope. Categorical variables such as SUB, HRU, LULC and SoilType have been eliminated from the regression analysis.

**Table 24.** Net benefit regression analysis results.

Model Variable	Variable Description	Function Slope <sup>28</sup>	Slope Stand. Error	y-Intercept	Intercept Standard Error	R <sup>2</sup> Value
<b><i>Economic Parameters:</i></b>						
WaterCost	Cost of water per unit volume [\$/m <sup>3</sup> ]	-1975.14	27.596	445.26	3.880	0.3714
Ky	Crop response factor	-44.76	17.191	264.94	15.564	0.0008
<b><i>.SBS SWAT Parameters</i></b>						
MEANEL	Average mean elevation of subbasin [cm]	0.04	0.009	183.52	9.088	0.0027
MINELEV	Average minimum elevation of subbasin [cm]	0.04	0.009	210.33	4.478	0.0023
MAXELEV	Average maximum elevation of subbasin [cm]	0.03	0.007	178.76	10.636	0.0024
PET	Potential evapotranspiration [mm]	0.27	0.555	-107.66	701.218	0.0000
ET	Actual evapotranspiration [mm]	1.82	0.084	-650.45	40.976	0.0672
SW	Soil water content	-3.43	0.127	504.03	10.529	0.1000
WSTRS	Temperature stress days	5.75	0.100	-13.41	5.280	0.3335
TMPSTRS	Temperature stress days	2.87	0.080	127.20	4.497	0.1657
NSTRS	Nitrogen stress days	0.39	0.059	207.84	5.595	0.0066
PSTRS	Phosphorus stress days	4.58	0.513	352.45	-19.027	0.1736
<b><i>Soil Parameters:</i></b>						
Ldepth	Top soil layer depth [mm]	0.62	0.084	69.87	21.419	0.0061
AWC	Available water capacity of the soil layer [mm water/mm soil]	-299.94	73.148	271.32	11.642	0.0019
HydCond	Hydraulic conductivity of top soil layer [mm/hr]	0.10	0.032	216.51	4.144	0.0010
pClay	Percent clay content of top soil layer [%]	-7.73	0.759	320.94	9.870	0.0118
pSilt	Percent silt content of top soil layer [%]	-0.58	0.158	245.76	6.391	0.0015

<sup>28</sup> All slope and intercept values indicated in Table 24 are significantly different from zero, within a probability of 99 %.



Model Variable	Variable Description	Function Slope <sup>28</sup>	Slope Stand. Error	y-Intercept	Intercept Standard Error	R <sup>2</sup> Value
pSand	Percent sand content of top soil layer [%]	0.70	0.139	188.70	7.815	0.0029
Ldepth2	Soil layer depth of second soil layer [mm]	0.05	0.009	183.49	8.020	0.0036
AWC2	Available water capacity of the second soil layer [mm water/mm soil]	-705.13	72.014	315.33	9.674	0.0109
HydCond2	Hydraulic conductivity of second soil layer [mm/hr]	0.25	0.044	207.93	4.198	0.0039
pClay2	Percent clay content of second soil layer [%]	-3.40	0.365	280.96	6.690	0.0099
pSilt2	Percent silt content of second soil layer [%]	-1.95	0.183	278.75	5.839	0.0129
pSand2	Percent sand content of second soil layer [%]	1.44	0.131	144.60	7.919	0.0137

The ANOVA results presented in Table 23 show that each of the variables included in the regression analysis were found to be statistically significant. Nevertheless the low R<sup>2</sup>-squared values associated with the regression analysis indicate that there is little direct correlation between any single variable and the net benefit results. This suggests that multiple variables may contribute, in varying ways, to the total net benefit associated with each HRU.

One possible exception is the cost of water, which has an obvious and direct impact on the resulting net benefit value. However, a linear regression was not clearly determined as indicated by the relatively low R<sup>2</sup>-squared value (0.37). This is primarily due to the varying price received and the crop response associated with each crop type.

Model results show that net benefit values are largely determined by the crop type. Mean values obtained for each crop type range from negative values in the case of sorghum to 600-700 \$/ha in the case of corn and soybean at a water cost level of 0.00 \$/m<sup>3</sup>.

Therefore, when the simulation data for each crop type is separated, a much more definitive regression is determined.

Table 25 presents the regression results for the net benefit verses water cost for each crop type. The results show strong correlation values, with R<sup>2</sup>-squared values ranging from 0.74 to 0.86. Regression results for corn and soybean show strong negative slope values indicating that raising water cost levels have the greatest impact on net benefit values for these two crops. Raising water cost levels have a less dramatic affect on wheat and sorghum, which are also associated with lower initial values, as indicated by the y-intercept values.

**Table 25.** Regression analysis of net benefit verses water cost for each crop type.

<b>Crop Type:</b>	<b>Variable:</b>	<b>Function Slope ± Std. Error</b>	<b>y- Intercept ± Std. Error</b>	<b>R<sup>2</sup> Value</b>
Corn	Water Cost [\$/m <sup>3</sup> ]	-2720.652 ±35.554	651.473 ±4.999	0.8256
Soybean	Water Cost [\$/m <sup>3</sup> ]	-2810.481 ±31.666	602.634 ±4.452	0.8643
Wheat	Water Cost [\$/m <sup>3</sup> ]	-1459.805 ±18.936	256.218 ±2.662	0.8277
Sorghum	Water Cost [\$/m <sup>3</sup> ]	-275.776 ±4.586	-25.913 ±0.644	0.7451

Other variables showed less significant correlation results even when crop simulations were separated by crop type, however, in general the results of the regression analysis indicate the relationship that each variable has on the predicted net benefit.

Variables associated with positive slope values indicate that the predicted net benefit

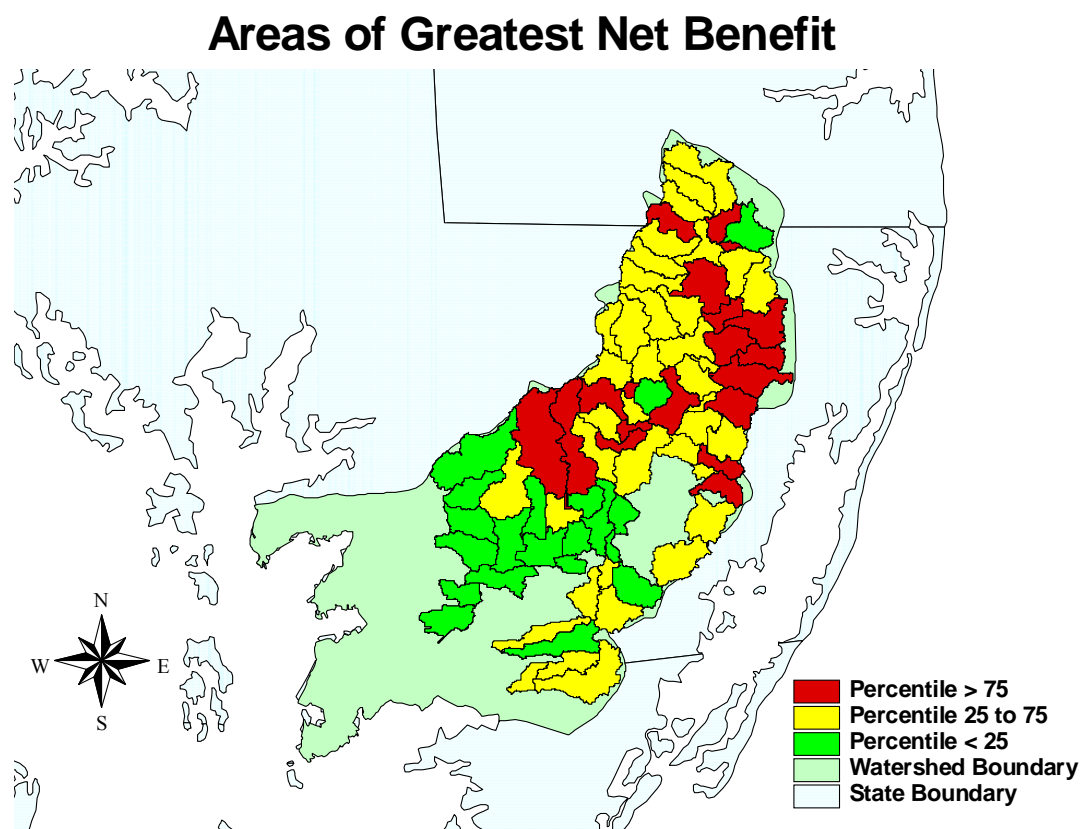
increases as the variable magnitude increases. ANOVA results indicate that irrigation application is more frequently prescribed for upland agricultural fields, accordingly, the regression results show that as the elevation values associated with a given agricultural field increase, so do the predicted net benefit values. Similarly, as the associated plant stresses increase (including water, temperature and nutrient stresses), so do the associated net benefit values. Likewise, as the soil parameters associated with more frequent irrigation prescription increase, such as the hydraulic conductivity and sand content, so does the associated net benefit.

Conversely, variables associated with less frequent irrigation prescription have a negative slope value indicating that the associated net benefit decreases as these variables increase. Results of the regression analysis show that the cost of water, the soil water content and available water are all associated with strong negative slope values, indicating that as these variables increase, the predicted net benefit value decreases. As already demonstrated, as the cost of water increases the associated net benefit decreases and therefore irrigation is less likely to be applied. Likewise, as the soil water content increases the usefulness and profit of irrigation decreases as reflected by the lower net benefit values. Soil physical characteristics that are typically associated with or allow for higher soil water content values include higher silt content and higher clay content values; the percent silt and percent clay variables are both associated with negative slope values, indicating that as these values increase the predicted net benefit of irrigation decreases.

As in the previous sections, each of the subbasins is ranked based upon the net benefit values determined in the *IrrigEcon* application. Figure 30 presents this

information spatially based on a rating system applied to each subbasin. Similar to the previous rating systems the score assigned to each subbasin is the sum of the scores of each HRU within the subbasin. The score attributed to each HRU at each water cost level is the net benefit value normalized based upon the relative size of the HRU. The net benefit value associated with each HRU is multiplied by area of the HRU and divided by the total area of all agricultural HRUs within the associated subbasin. The subbasins are then ranked based upon the overall score received; those subbasins with the highest rank are associated with areas that profit most for irrigation installation.

Figure 30 presents a spatial delineation based upon the net benefit rank received by each subbasin. Subbasins within the 75<sup>th</sup> percentile or greater are associated with above average net benefit returns; subbasins within the 25<sup>th</sup> to 75<sup>th</sup> percentile are categorized as average; and subbasins ranked less than the 25<sup>th</sup> percentile profit least for the installation of irrigation equipment.



**Figure 30.** Spatial delineation of subbasin irrigation net benefit scores base upon applied rating system.

#### **Environmental Impact of Irrigation:**

The final objective of this project is to determine the environmental impact of irrigation on local bodies of water. The information that follows assesses the modeled environmental impact, under irrigated and non-irrigated conditions, with particular emphasis on the export of the various forms of nitrogen and phosphorus, the primary contributors to the eutrophication of natural waters. The values reported represent the calculated annual nutrient transport volume of 177 HRU's within the watershed simulated over a 20-year period using model generated weather data.

In general, there is great variability between agricultural fields within a given watershed, in terms of both the quantity and type of fertilizer being applied, as well as the timing and distribution of the fertilizer application, depending upon the initial fertilizer levels/soil conditions, the crop being grown at each farm site and farm manager preferences. Moreover, fertilizer application will inevitably involve soil testing to determine the exact needs of the farm prior to application.

However, in the absence of this specific information, and for the sake of model simplicity, both a 'high' and 'low' fertilizer application schedule based on the Maryland Cooperative Extension (2002) recommendations for specific crops and soil conditions is applied to all fields as described in the *Methods and Procedures* section of this report. This approach simplifies the calculation procedures, allowing for direct comparison between all simulations. For comparison purposes, the same quantity of fertilizer is applied under both the irrigated and non-irrigated scenarios, even though higher yields, and thus higher nutrient demands, are expected under irrigated conditions.

In each scenario involving irrigation, irrigation is applied to all HRU's in which an agriculture crop is produced where irrigation is initiated by the SWAT model as a management practice based on the ratio of actual to potential growth given the water availability, as described in the *Methods and Procedures*. For the purposes of this report, this ratio is referred to as the irrigation factor, and defines the set irrigation intervention point for each irrigation event for each SWAT simulation. In this comparison, a series of 14 irrigation set points are used, representing various levels of irrigation intensity corresponding to different levels of actual to potential growth rates ranging from 0 to 1.0.

All scenarios have the same weather pattern attributed to them with the average annual precipitation for all HRU's of 1034 mm (40.7 inches). The total applied irrigation water volume to achieve full growth is averaged at just less than 170 mm annually (168 mm/yr), decreasing with each irrigation factor used. As a result irrigation water contributes at most 16.3 % of the total annual overhead water yield entering each agricultural HRU.

*Irrigation Application Effects:*

As described above, two irrigation series were conducted, representing both a 'high' and 'low' fertilizer application schedule typical of the region for each crop and soil type. In order to draw comparisons between the two fertilizer application rates, a plot of some of the key variables associated with each series is presented below, and labeled as either 'Low Fertility' or 'High Fertility,' referring to the more conservative or liberal fertilizer application schedules applied as defined in the *Methods and Procedures* section of this study. In general, the same patterns emerge over a range of irrigation intensities for each variable considered, although the magnitude and degree of variability differs, between the 'high' and 'low' fertilizer application rates.

Figure 31 and Figure 32 plot the average annual irrigation water demand corresponding to each irrigation factor simulated, for the low and high fertilizer application rate, respectively. Also included in the plot is the average number of water stress days for each irrigation schedule simulated. A water stress day is calculated as any day in which the ratio of actual plant water uptake to potential water demand falls below 0.95.

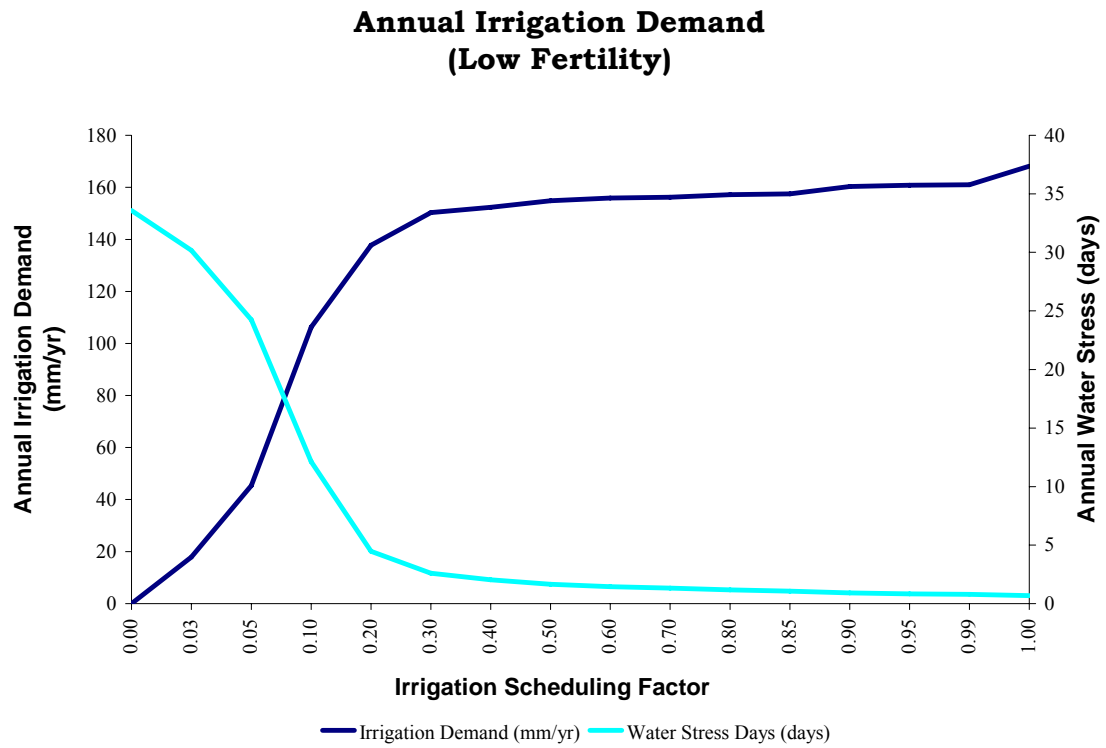
In the graphs below as the *Irrigation Scheduling Factor* (ISF) approaches 1 the actual growth rate achieved approaches the potential growth rate, resulting in zero water stress days. As the ISF approaches 0, which indicates no applied water despite the severity of the water demand and the resulting diminished growth rate, the number of water stress days increases dramatically up to the maximum number of days within the growing season. The irrigation scheduling factor determines the point at which an irrigation event is triggered, and is defined as the ratio of the actual growth rate to the potential growth rate of the crop. Once the ratio of the actual to potential growth rate of the crop falls below the irrigation scheduling factor an irrigation event is triggered.

$$ISF = \frac{ActualGrowth}{PotentialGrowth} \quad (30)$$

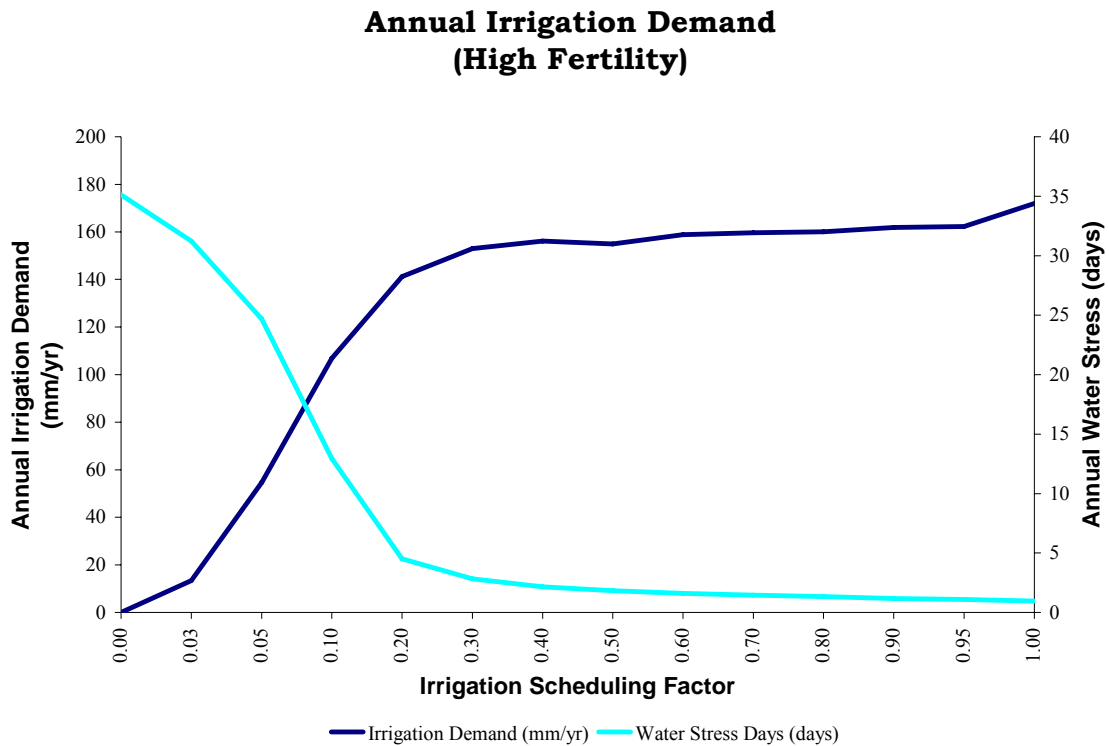
If     ISF = 1.0     (no water stress days are recorded)

If     ISF = 0.0     (large number of water stress days are recorded)





**Figure 31.** Annual irrigation water demand and corresponding number of water stress days for each irrigation intensity level simulated using the lower fertilizer application rate.



**Figure 32.** Annual irrigation water demand and corresponding number of water stress days for each irrigation intensity level simulated using the higher fertilizer application rate.

The two plots above show a sharp rise in irrigation water demand for an irrigation factor of up to 0.30, followed by a gradual rise in irrigation demand beyond that point. This pattern is paralleled by the corresponding decrease in the number of water stress days for simulations associated with higher irrigation factors.

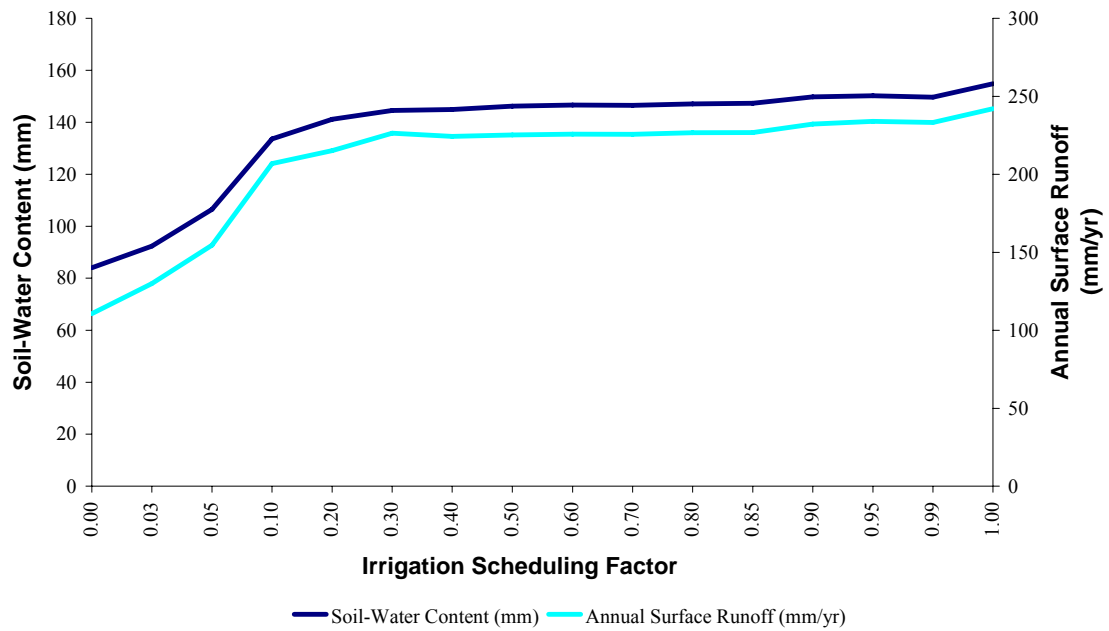
Contrasting the two irrigation simulation sets, the higher fertilizer rate results in only a slight increase in the total water demand; reaching an average maximum of 172 mm/yr when compared to the average maximum of nearly 168 mm/yr under the reduced fertilizer application schedule. A corresponding slight increase is seen in the number of water stress days, with a maximum average of 33.6 stress days observed with the low

fertilizer application rate, compared to a maximum of 35.1 stress days seen with the higher fertilizer application rate, when no irrigation is applied.

The results indicate that as the quantity of fertilizer is increased, the potential growth of the crop increases such that insufficient water is more likely to be a limiting factor to the growth of the plant resulting in a higher number of water stress days, thereby increasing the overall water demand to a marginal degree. Nevertheless, this change is slight given the relatively substantial increase in fertilizer application between the two irrigation simulation sets (25% increase in applied nitrogen and 200% increase in applied phosphorus between the two irrigation series).

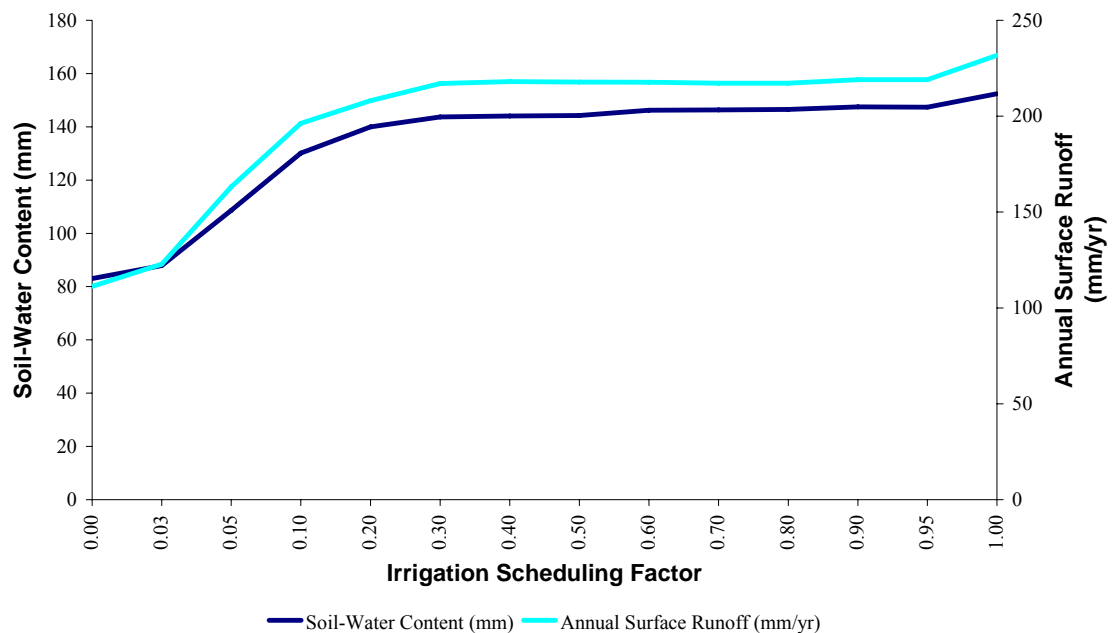
Under maximum irrigation conditions the average soil water levels nearly double when compared to non-irrigation conditions for both simulation sets, increasing from an average for both sets of 83 mm of water to 153 mm of water, thereby allowing for higher growth rates. However, the higher soil water levels lead to an even more dramatic increase in the total annual surface runoff values for each HRU; increasing from an average of 111 mm/yr without irrigation to a maximum average of 237 mm/yr with full irrigation, a 214% increase. This parallel increase in annual runoff values is seen in Figure 33 and Figure 34, which plot the average soil water levels [mm] and the corresponding annual runoff [mm/yr] versus the irrigation intensity for both the 'high' and 'low' fertilizer application schedules.

### Soil-Water and Surface Runoff Relationship (Low Fertility)



**Figure 33.** Average soil-water content and corresponding annual surface water runoff versus irrigation intensity associated with the lower fertilizer application rate.

### Soil-Water and Surface Runoff Relationship (High Fertility)



**Figure 34.** Average soil-water content and corresponding annual surface water runoff versus irrigation intensity associated with the higher fertilizer application rate.

This drastic rise in surface runoff volumes is due to an acceleration in the time required before runoff begins, when comparing irrigated and non irrigated conditions. Under irrigated conditions runoff occurs sooner during, and immediately following, periods of heavy precipitation due to the decreased capacity of the soil profile to absorb additional water (resulting in a net reduction in the initial abstraction associated with each precipitation event), as the average soil water levels are considerably higher due to regular irrigation application.

However, it should be noted that when compared separately, the increase in runoff associated with simulations with irrigation verses without is slightly less in the simulations with the higher fertilizer applications, due to the increase in growth of the crop and the subsequent increase in the evapotranspiration rates. On average, surface

runoff increases from 110.6 mm/yr to 242.1 mm/yr (a 218% increase) under low fertilizer application conditions; compared to an average increase from 111.2 mm/yr to 231.7 mm/yr (a 208% increase) under the high fertilizer application schedule.

When modeling agricultural irrigation demand, the soil-water content of the soil remains relatively high at all times, and an irrigation event is scheduled whenever soil-water levels drop to an unacceptable threshold, limiting plant growth. As a result, once precipitation ensues soils become saturated sooner, resulting in the onset of runoff earlier in the irrigated simulation when compared to the non-irrigated simulation (with an irrigation scheduling factor = 0.0). As will be seen in the figures that follow, an increase in the surface runoff leads to a subsequent increase in sediment transport and associated nutrient transport with the increased volumes of surface runoff.

This apparent negative environmental impact can be mitigated in actual practice depending on the astute discretion of the farm manager, which can not be easily and adequately reflected in the current model simulations. This demonstrates a limitation in the irrigation simulation in that the irrigation scheduling is blind to future weather forecasts, which may contribute to the decision making process observed in actual practice with regards to irrigation scheduling and application.

In actual practice if a precipitation event is anticipated, based on local weather forecasts, the farm manager may opt to turn off irrigation equipment several days in advance, in anticipation of oncoming rains, even if the soil-water content levels fall below the set irrigation intervention point. Irrigation events scheduled in the model do not benefit from this future forecast and decision-making process. Therefore, an

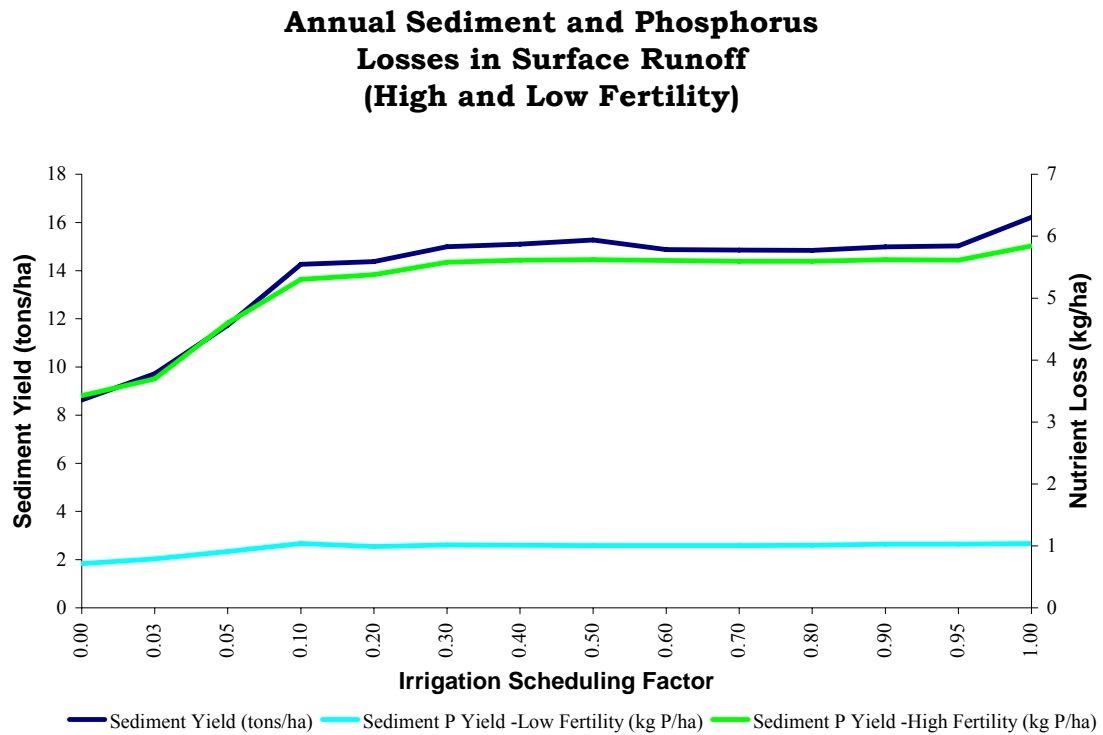
irrigation event may be applied, based on time specific soil moisture levels, even if precipitation is simulated the following day or time-step.

Nevertheless, this management decision process will ultimately reduce the sediment and surface runoff volumes, along with the associated nutrient losses under actual farm managed irrigated conditions when compared to model irrigation simulations. In the current modeling scenario irrigation scheduling is indiscriminant to future climatic events, and is based solely on conditions prior to the scheduled irrigation event. However, even with the incorporation of this management decision making process, surface runoff volumes, and subsequently sediment yields, are expected to remain substantially higher than surface runoff volumes and sediment yields under non-irrigated conditions.

The increase in the overall runoff volume leads to higher sediment yields due to higher erosion rates. The higher runoff volumes result in higher nutrient yields associated with the surface runoff, particularly in the form of sediment bound phosphorus. One of the simulation settings for the operation of SWAT allows for the user specified distribution of applied fertilizer throughout the soil profile. In the case of these model simulations 50% of the applied fertilizer is distributed within the top 10 mm of the soil profile. However, alternative application methods, may result in higher quantities of fertilizer being distributed at deeper soil levels resulting in less nutrient loss due to surface runoff.

Figure 35 plots the annual sediment yields, which is an estimate of the total sediment in the watershed being transported from agricultural fields into the reaches and streams as a result of surface runoff. Also included in this graph is the sediment bound

phosphorus loss values, which are tightly correlated to sediment yield. The results show that sediment and phosphorus yields increase with higher runoff values associated with higher irrigation intensities.



**Figure 35.** Annual sediment yield and phosphorus loss versus irrigation intensity associated with ‘high’ and ‘low’ fertilizer application rates.

Contrasting the high and low fertilizer application simulations the same general pattern emerges, characterized by a sharp increase in the tightly associated sediment and sediment bound phosphorus transport levels seen with the onset of irrigation. However, an even more drastic increase in the transport of sediment bound phosphorus is seen with the higher fertilizer application rate, nearly a two-fold increase; while the actual quantities of sediment transport remain comparable, ranging from just above 8 tons

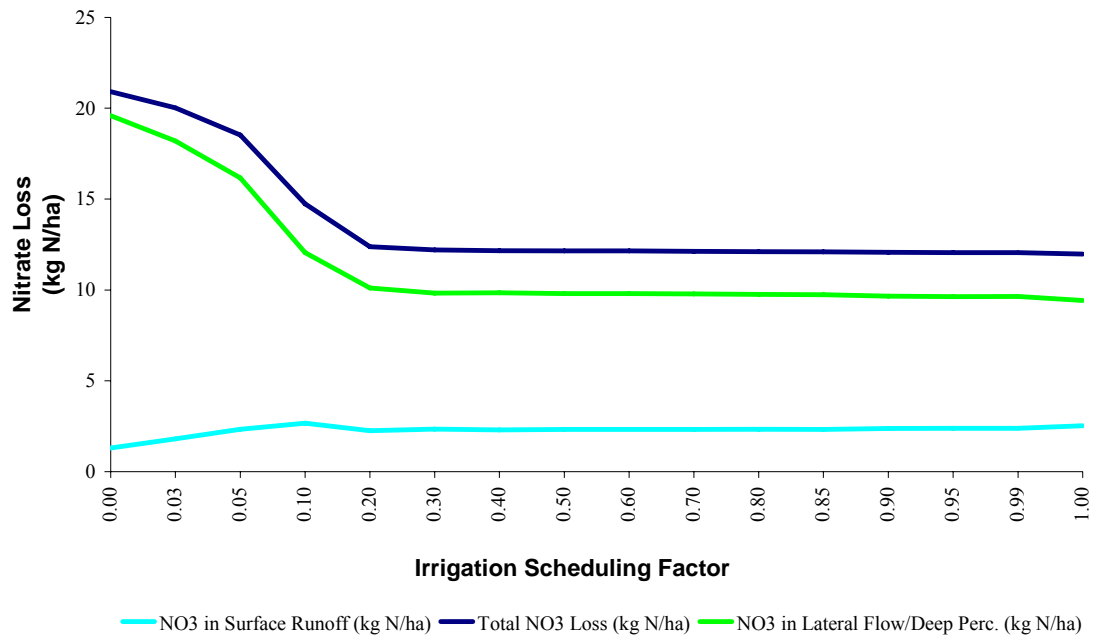


per/ha up to 16 tons/ha with a slight decrease in sediment transport rates seen with the higher fertilizer application simulations due to the slight decrease in runoff volumes.

As expected, the higher phosphorus application rates result in a greater excess of sediment bound phosphorus. Under the 'low' fertilizer application rates the average annual phosphorus transport quantities range from 1.83 kg P/ha with no irrigation to 2.68 kg P/ha, a 46% increase, under fully irrigated conditions. These quantities nearly double under the higher fertilizer application rates, ranging from an annual average of 3.43 kg P/ha to 5.84 kg P/ha, a 73% increase.

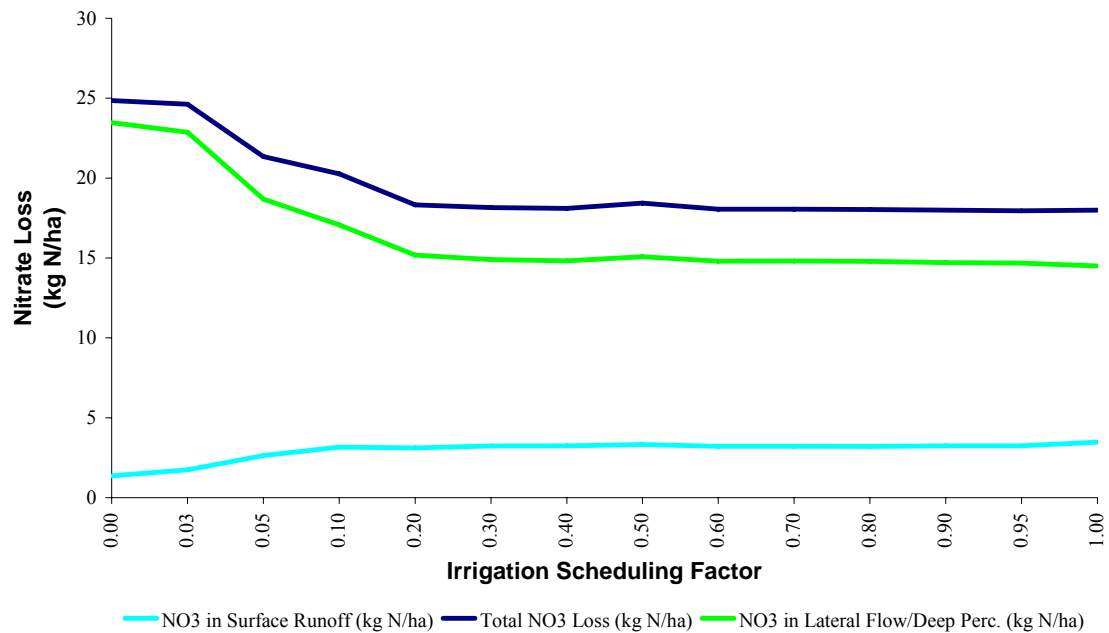
Figure 36 and Figure 37 plot the total nitrate export associated with each irrigation factor, as well as the individual nitrate components associated with surface runoff, lateral flow and total nitrate loss. The values presented in the figures below represent the average total of nitrate being exported per hectare for all HRU's in which an agricultural crop is produced. Leached nitrate levels were negligible at all irrigation levels and therefore not included in the figures below. Nitrate export associated with leaching did increase slightly with higher irrigation intensities, but remained insignificant overall.

### Total Annual Nitrate Export (Low Fertility)



**Figure 36.** Average nitrate export over the entire watershed associated with the ‘low’ fertilizer application rate.

### Total Annual Nitrate Export (High Fertility)



**Figure 37.** Average nitrate export over the entire watershed associated with the ‘high’ fertilizer application rate.

As would be expected, higher nitrate losses are likewise associated with higher surface runoff values. However, the higher nitrate loss due to higher runoff volumes is offset by a more significant drop in nitrate loss associated with subsurface lateral flow when compared to non-irrigated conditions, resulting in a net reduction in the total nitrate export out of the HRU of up to 42.6 %, under maximum irrigation conditions (ISF = 1.0) for the ‘low’ fertilizer application simulations; and a 27.4% reduction in the total nitrate export under the ‘high’ fertilizer application conditions.

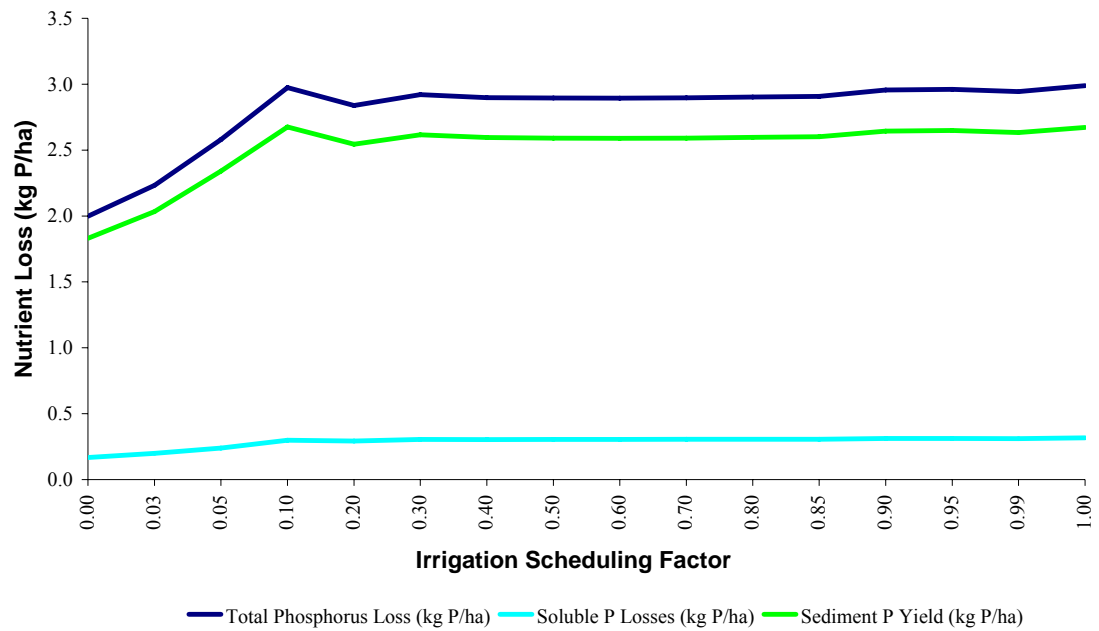
This drop in nitrogen transport out of the HRU is readily seen, even at very low irrigation application intensities. In both simulation sets nearly the entire potential nutrient reduction is achieved at an irrigation scheduling factor of 0.30. In the case of the ‘low’ fertility simulations a nitrogen reduction of 41.6% (compared to a maximum of

42.6%) is achieved at an irrigation factor of 0.30; while a total nitrogen reduction of 25.8% (compared to a maximum of 27.4 %) is achieved during the 'high' fertility simulations at the same irrigation level.

The observed decrease in nitrate export as a result of decreased pore water concentrations of soluble nitrate in the lateral flow is expected, due to the increase in plant nitrate uptake achieved as a result of higher growth rates associated with the higher irrigation intensities. A corresponding increase in nitrate export seen with surface runoff is attributed to the significantly higher runoff volumes associated with irrigation scheduling when compared to non-irrigated conditions, as discussed above. However, the significant decrease in the transport of nitrate with lateral flow volumes results in a net decrease in the overall transport of nitrate out of the HRU despite the increase in nitrate transport associated with higher runoff volumes.

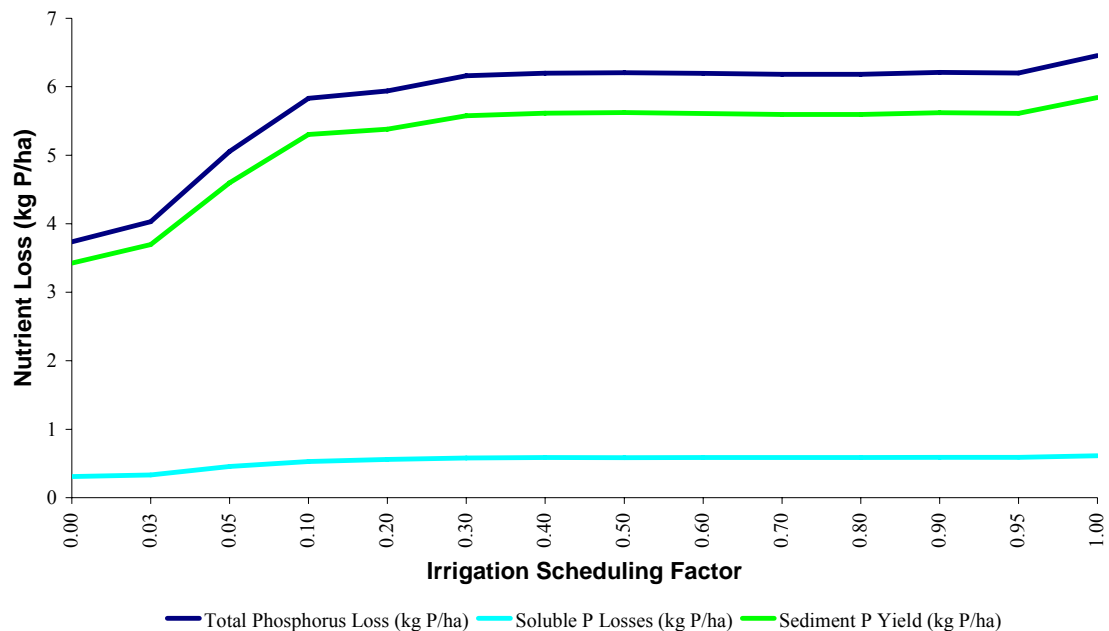
In contrast an increase in phosphorus export is observed with increasing irrigation intensities in both the high and low fertilizer application simulations, due primarily to the tight association of sediment bound phosphorus with sediment yield. The export of soluble phosphorus also increased with irrigation intensity although remained far less significant than phosphorus associated with sediment yield. Figure 38 and Figure 39 show the total phosphorus loss, as well as the individual components of sediment bound phosphorus yield and the combined export of soluble phosphorus either through surface runoff, lateral flow or leaching, for the 'low' and 'high' fertilizer application simulations, respectively.

### Total Annual Phosphorus Export (Low Fertility)



**Figure 38.** Phosphorus exports over the entire watershed versus irrigation intensity associated with the 'low' fertilizer application rate.

### Total Annual Phosphorus Export (High Fertility)



**Figure 39.** Phosphorus exports over the entire watershed versus irrigation intensity associated with the ‘high’ fertilizer application rate.

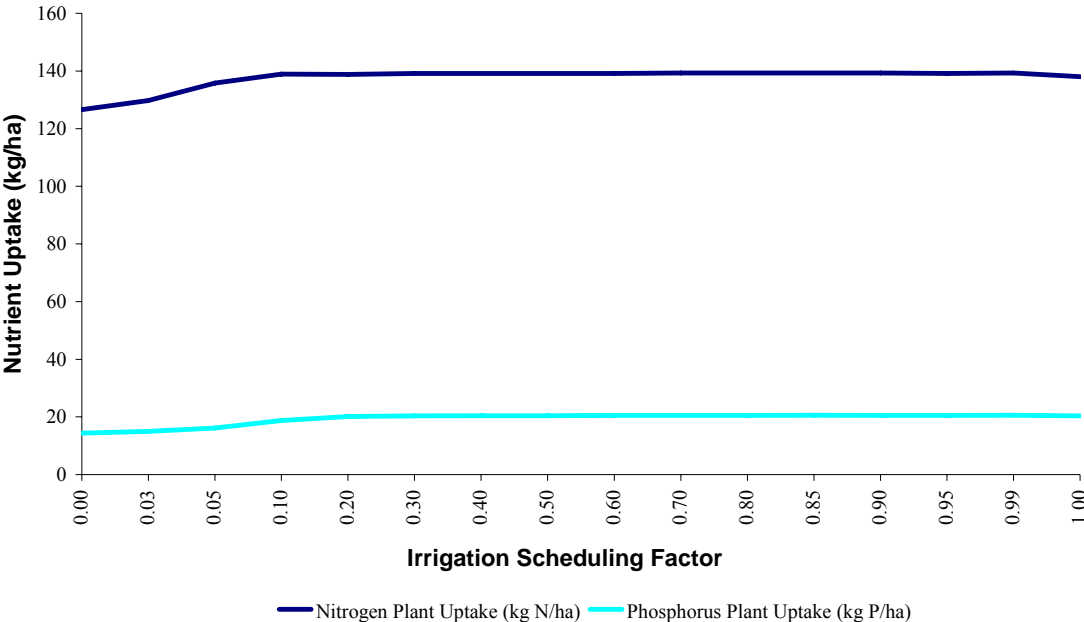
In contrast to nitrate export, a net reduction is not seen with phosphorus levels. Both sediment bound and soluble phosphorus export levels increased with increasing irrigation levels. The dramatic increase in sediment export due to higher runoff levels clearly explains the increase in sediment bound phosphorus levels. Likewise, increases in the export of soluble phosphorus levels are to be attributed to higher runoff and leaching volumes, however, unlike nitrate export, soluble phosphorus concentrations are not significantly reduced due to increased plant uptake. This may be attributed to the natural balance achieved between soluble and sediment bound phosphorus pools.

Unlike nitrate concentrations, soluble phosphorus concentrations remain in constant equilibrium with excess insoluble bound phosphorus, and are therefore continually replenished as soluble phosphorus concentrations are consumed due to plant

uptake. This continual replenishment of soluble concentrations does not occur in the case of nitrate, and therefore, plant uptake can have a more significant impact on limited nitrate concentrations.

In the cases presented above, nitrogen and phosphorus export values level off once an irrigation factor of 20 to 30 percent is achieved. This pattern is repeated in the nutrient uptake and biomass production associated with both the 'high' and 'low' fertilizer application schedules. Figure 40 and Figure 41 show the total plant nitrogen and phosphorus uptake versus irrigation intensity for both simulation sets. In both cases nitrogen and phosphorus uptake increased significantly with increasing irrigation intensity. Under 'low' fertilizer application conditions the mean nutrient uptake rate approaches 144.3 kg/ha for nitrogen and 19.5 kg/ha for phosphorus; and approaches 162.9 kg/ha for nitrogen and 20.3 kg/ha for phosphorus with the 'high' fertilizer application simulations.

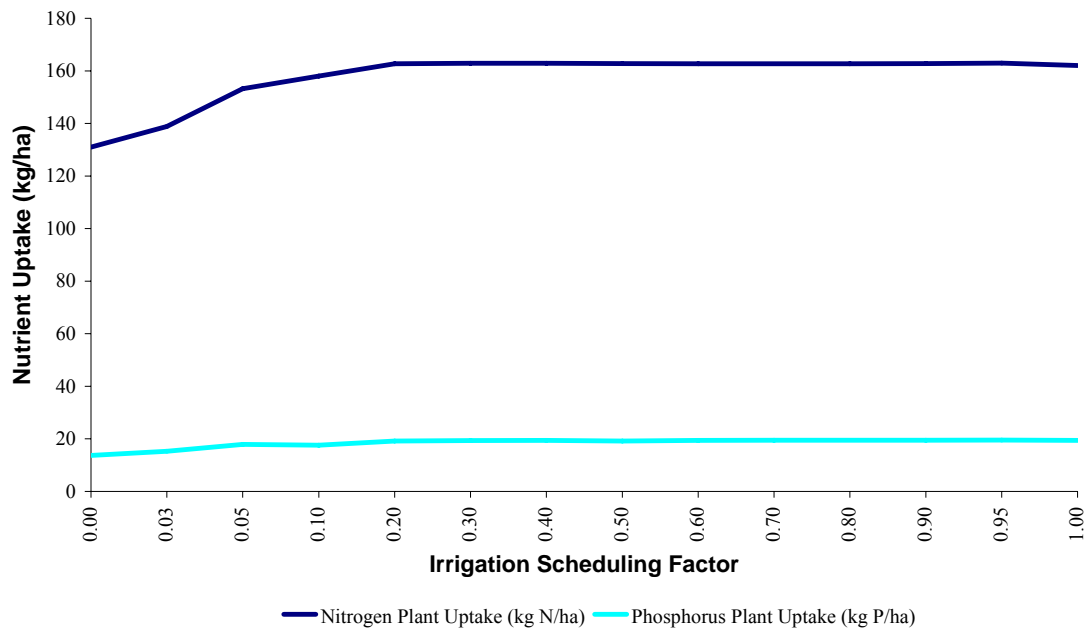
### Annual Plant Nutrient Uptake (Low Fertility)



**Figure 40.** Plant nitrogen and phosphorus uptake versus irrigation intensity associated with the lower fertilizer application rate.



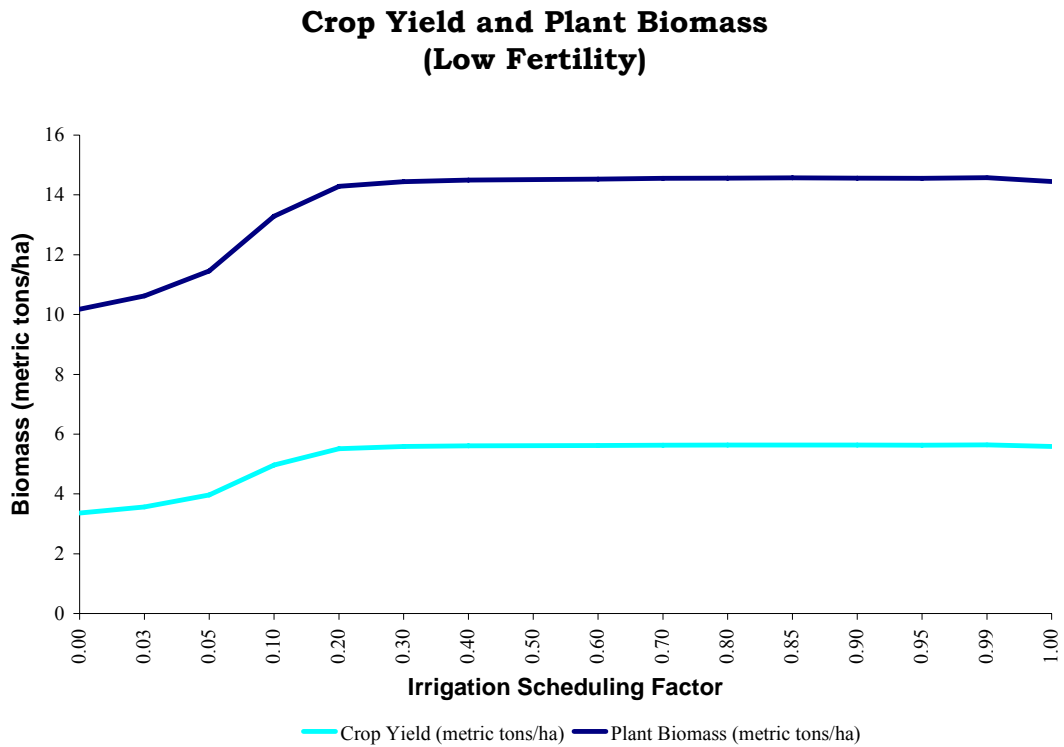
### Annual Plant Nutrient Uptake (High Fertility)



**Figure 41.** Plant nitrogen and phosphorus uptake versus irrigation intensity associated with the higher fertilizer application rate.

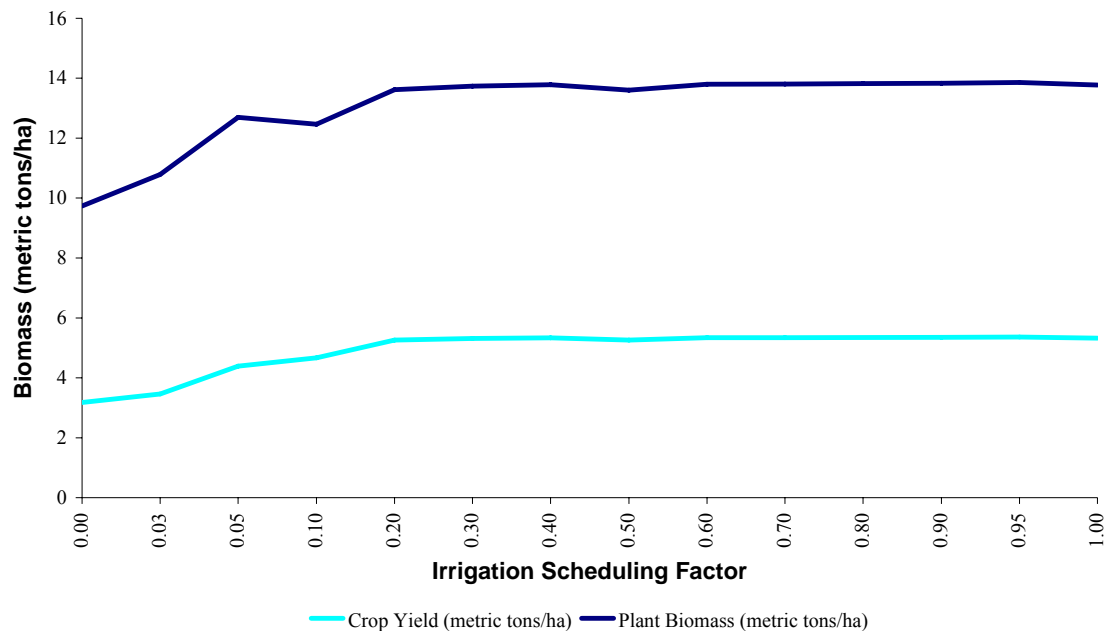
This rise in nutrient uptake is directly paralleled by an increase in the total plant biomass and crop yield as seen in Figure 42 and Figure 43, although only a marginal change in the maximum biomass and yield is seen between the two simulation sets. This marginal change, despite the significant difference in the fertilizer application rates between the irrigation simulation sets, may indicate that the fertilizer application rate is not as significant a limiting factor in plant growth when compared to water availability. Biomass and yield increased 67.8% and 43.2%, respectively, between the non-irrigated and fully-irrigated simulations when the ‘low’ fertilizer application schedule is applied; and increased 68.8% and 42.4%, respectively, when the ‘high’ fertilizer application schedule is applied. On average, only a 1% difference for both biomass and yield

production is attributed to the difference in nutrient application between the two simulation series at full irrigation.



**Figure 42.** Biomass production and crop yield versus irrigation intensity associated with the lower fertilizer application rate.

### Crop Yield and Plant Biomass (High Fertility)



**Figure 43.** Biomass production and crop yield versus irrigation intensity associated with the higher fertilizer application rate.

The figures above show relatively insignificant increases in crop yields above an irrigation scheduling factor of 0.2 to 0.3. This seems to suggest an optimal irrigation management scenario in which a relatively low irrigation intensity level is maintained, while still maintaining desired yield levels.

This is consistent with data presented previously concerning the irrigation water demand associated with the maximum net benefit. The data presented in Figure 19 through Figure 22 demonstrate that at high water cost levels low irrigation levels are the most economically favorable; while a more dramatic increase in irrigation intensity, resulting in a marginal increase in productivity, is only profitable when water cost are low. This transition point between high and low irrigation intensity levels, associated

with Figure 19 through Figure 22 varies depending on the price received for the crop and yield response to deficit irrigation or drought conditions.

*Statistical Analysis of Environmental Impact Results:*

The paragraphs above present graphical information and discuss general trends and observances without getting into detailed statistical analysis of the data. The paragraphs that follow discuss the analysis of variance results associated with the data above, and qualify the general trends observed. All statistical analysis reported herein has been conducted using a statistical analysis software package, *SAS Version 9.1*.

A caveat should be made prior to discussion of statistical results, in that the data analyzed represents model calculated values, and not actual field measured data. In this regard, two important considerations should be borne in mind before conducting a statistical review of the data.

The first point to consider is that measured field data normally contains a great deal of variability due to sampling variance, including error in measurement and testing due to equipment biases and handling, and variance due to field conditions and associated heterogeneities, all of which will vary independent of the applied treatment, which in this case is the applied irrigation level.

This differs from the circumstances revolving around modeled data. In the case of modeled data there are primarily two sources of error. The first source of error is associated with the input data, in terms of both the accuracy and resolution of the spatial information, as well as the accuracy of the physical properties and descriptive parameters associated with the terrain, land use and soils input data, despite the fact that the input data included is obtained from reputable governmental sources and is considered to be

the best available for the scale used in this study. The second source of error is introduced during model calculations resulting from model assumptions made and the equations used. Although SWAT is considered a reasonable model, all model calculations and procedures make assumptions or fail to consider all relevant processes and effects, and can, therefore, only be considered estimates of the true value found in the field.

Both of these sources of error are not represented in the statistical data obtained from modeled values. Values are calculated for each HRU over a series of irrigation intensities, and in each case the identical input data is used, as are the identical calculation procedures and algorithms, which are used to estimate the nutrient parameters sought. As a result, the error and biases due to inaccurate input data and calculation procedures are introduced into the resultant output values in an identical manner for each simulation.

The statistical analysis is unable to discern this error from the data alone as no variance is seen. Rather the variance observed between model sample values results from the calculated effects of irrigation given the distinct terrain, soil and hydrological parameters associated with each HRU, as well as the calculation procedures used. As a result the modeled data appears to be highly precise, but may lack in accuracy due to the errors associated with the input data and calculations that can not be easily estimated.

The second point to consider, when analyzing modeled data, is that, due to limitations in resources, field analysis is often hindered by sampling limitations which do not encumber modeled data. Field analysis may be limited to select fields, with a limited number of treatments and samples. The sampling of all agricultural fields throughout a

watershed and the summation of nutrient transport throughout the year over a twenty-year period would be almost impossible and cost prohibitive in actual practice, although this is easily accomplished through computer modeling.

As a result, modeling may generate enormous amounts of data not feasible with field analysis alone. The enormity of the resulting sampling sizes, possible with computer models, will therefore contribute significantly to the apparent data confidence when conducting statistical analysis. Whereas, realistic limitations in sample sizes associated with field analysis may result in less statistical confidence when compared to modeled data. Moreover, it will be a near impossible task to obtain fully representative samples when hand collected from agricultural fields spread over an extended area, such as a USGS hydrological cataloging unit (watershed). In contrast, using computational models, large quantities of data including representational values for all agricultural regions over extended spatial domains and periods of time are easily achieved, resulting in apparently higher confidence intervals.

As a result of the lack of variance associated with model input data and calculation error, and the sheer number of sample values generated, differences in treatment effects are readily seen with an apparent high degree of confidence. This same level of confidence in treatment effects is unlikely under field sampling conditions alone. However, as the objective of this portion of the study is to lend justification for or against further field study of the long-term effects of irrigation on nutrient transport into rivers and streams, the general trends observed from computer modeling is more than sufficient as a preliminary review. Albeit, the caveats mentioned above should be remembered when considering some of the highly significant differences that may be observed with

modeled data, which may be, from a practical perspective, may not be meaningful or barely, if at all, detectable in the field.

That being said a significant difference was observed for nearly all simulated parameters (surface runoff, sediment yield, plant biomass, crop yield, phosphorus uptake, nitrogen uptake, sediment bond phosphorus, soluble phosphorus, nitrate in surface runoff, total nitrate transport, and total phosphorus transport), between irrigated and non irrigated conditions within a 99% confidence interval, with the exception of nitrate leached past the root zone. In this case no significant difference was observed primarily due to the low nitrate concentrations and small leaching volumes values associated with both irrigated and non-irrigated conditions.

Table 26 presents the reported *t*-value and associated probability for each of the parameters simulated with and without irrigation. In this case, data obtained from both the ‘high’ and ‘low’ fertility application simulations have been combined. It is felt that this pooling of the simulation data is justified given the identical trends found in both simulation series as discussed above, despite slight difference in the output parameter magnitude between the high and low fertilizer simulations.

In the statistical analysis the ‘Folded-F’ method is used to determine if variance between each treatment group is equal or unequal. In the cases where variances were found to be equal, within a 99% confidence interval, the pooled variance method is used to calculate the *t-value* and the associated probability; in cases where the variance is found to be unequal the more conservative ‘Satterthwaite’ method is used to calculate the *t-value* and associated probability. Each of these calculation methods is conducted in *SAS* (Statistical Analysis Software, 2005).

**Table 26.** Calculated *t*-values and the associated probability values for comparison of variables between simulations with and without irrigation for the combined dataset of the ‘low’ and ‘high’ fertilizer application simulations.

<b>Variable:</b>	<b>Description:</b>	<b>Variance:</b>	<b><i>t</i>-value:</b>	<b>Probability:</b>
IRR	Irrigation Volume Applied	Unequal	172.77	<0.0001
W_STRS	Water Stress Days	Unequal	-74.27	<0.0001
SW	Soil Water Content	Unequal	36.73	<0.0001
SURQ	Surface Runoff	Equal	48.99	<0.0001
SYLD	Sediment Yield	Equal	6.55	<0.0001
BIOM	Plant Biomass	Unequal	51.79	<0.0001
YLD	Crop Yield	Unequal	60.22	<0.0001
PUP	Phosphorus Uptake	Unequal	51.61	<0.0001
NUP	Nitrogen Uptake	Unequal	27.13	<0.0001
SEDP	Sediment Bound Phosphorus	Unequal	18.29	<0.0001
SOLP	Soluble Phosphorus	Unequal	31.79	<0.0001
NSURQ	Nitrate in Surface Runoff	Unequal	37.75	<0.0001
NLATQ	Nitrate in Lateral Flow	Unequal	-15.07	<0.0001
NO3L	Leached Nitrate	Equal	1.56	0.1177
NTOTAL	Total Transported Nitrate	Unequal	-15.07	<0.0001
PTOTAL	Total Transported Phosphorus	Unequal	19.84	<0.0001

As discussed in the previous section, variables associated with the growth and vitality of the crop, including: plant biomass, crop yield, and phosphorus and nitrogen uptake, all show strong positive increases with irrigation when compared to simulations without irrigation, indicating that these values increase with increased irrigation intensity. This general trend is clearly supported in the graphical information presented in the previous section. However, changes in nutrient transport quantities are mixed.

The transport of phosphorus in both soluble and sediment bound forms is greater under irrigated conditions when compared to non-irrigated conditions. Increases in phosphorus transport is paralleled by an increased surface runoff and sediment yield under irrigated conditions. As a result, the net transport of phosphorus out of the HRU is



increased, despite the simultaneous increase in phosphorus uptake under irrigated conditions, as indicated by the strong *t*-value and associated probability ( $<0.0001$ ).

In contrast nitrogen transport processes were mixed. Nitrogen transport through surface runoff increased under irrigated conditions due to higher runoff volumes, while nitrogen transport is decreased in lateral flow with higher irrigated intensities. This, combined with the increase in nitrogen uptake by the crops under irrigated conditions, results in a net decrease in the amount of nitrogen leaving the HRU with the higher irrigation intensities.

Table 26 broadly compares parameter values with and without irrigation irrespective of irrigation intensity. However, the plots presented previously in this section clearly show rapid increases or decreases in parameter values at lower irrigation levels but remain fairly constant, showing little significant difference, at higher irrigation intensities. Therefore, an attempt is made to characterize this nonlinear response by use of regression analysis.

The objective of regression analysis is to determine the function and equation parameters that best fit a given set of data (NLREG, 2005). This process involves the selection of the form of the equation (linear, exponential, natural log etcetera), and the determination of the equation parameter values that best fit the data set that is being described. This is done by the calculation of an adjusted R-squared value, which is a measure of the closeness of the data values to the regression analysis line.

Table 27 lists the adjusted R-squared values, calculated in *SAS*, obtained for the linear regression as well as the log transform and square root transform of the SWAT calculated values. The regression model with the highest adjusted R-squared value is

highlighted in the table below and is considered to be the best fit equation for the combined data of both the ‘low’ and ‘high’ fertilizer application simulations. Regression analysis results are not included on the leached nitrate levels, as the statistical *t*-test comparison did not indicate a statistical difference between leached nitrate levels between simulations with and without irrigation.

The equation with the highest adjusted R-squared value indicates the greatest correlation between the data set values and the regression equation. An adjusted R-squared value of 1.0 implies an absolute correlation between the data set and the regression equation; or rather implies that all data points fall upon the regression equation line.

**Table 27.** Adjusted R-Squared values for combined model parameters versus irrigation intensity showing three regression model comparisons.

<b>Variable:</b>	<b>Description:</b>	<b>Linear Reg. Adj. R-Sq.</b>	<b>Natural Log Transform Adj. R-Sq.</b>	<b>Square Root Transform Adj. R-Sq.</b>
IRR	Irrigation Volume	0.5469	0.3376	0.4569
W-STRS	Water Stress	0.5532	0.7737	0.6714
SW	Soil Water	0.2383	0.2024	0.2725
SURQ	Surface Runoff	0.3140	0.2180	0.3044
SYLD	Sediment Yield	0.0104	0.0222	0.0273
BIOM	Plant Biomass	0.4008	0.2874	0.3988
YLD	Crop Yield	0.4486	0.3288	0.4418
PUP	Phosphorus Uptake	0.4006	0.2873	0.3985
NUP	Nitrogen Uptake	0.1042	0.0444	0.1048
SEDP	Sediment Bound Phosphorus	0.0494	0.0176	0.0549
SOLP	Soluble Phosphorus	0.1078	0.0213	0.1096
NSURQ	Nitrate in Surface Runoff	0.1114	0.0160	0.1292
NLATQ	Nitrate in Lateral Flow	0.1280	0.0330	0.0993
NTOTAL	Total Transported Nitrate	0.0938	0.0301	0.0779
PTOTAL	Total Transported Phosphorus	0.0577	0.0200	0.0636

For the purpose of comparison the same regression analysis is conducted on both the ‘low’ and ‘high’ fertilizer application series separately, as presented in Table 28 and Table 29. Although the general trends remained the same and the adjusted R-squared values were similar, not all variable plots were best described by the same transform as seen in the tables below.

**Table 28.** Adjusted R-Squared values for the model parameters of the ‘low’ fertilizer simulation series versus irrigation intensity showing three regression model comparisons.

<b>Variable:</b>	<b>Description:</b>	<b>Linear Reg. Adj. R-Sq.</b>	<b>Natural Log Transform Adj. R-Sq.</b>	<b>Square Root Transform Adj. R-Sq.</b>
IRR	Irrigation Volume	0.5390	0.3529	0.4574
W-STRS	Water Stress	0.5622	0.8083	0.6891
SW	Soil Water	0.2106	0.1867	0.2503
SURQ	Surface Runoff	0.3369	0.2527	0.3272
SYLD	Sediment Yield	0.0075	0.0167	0.0222
BIOM	Plant Biomass	0.4570	0.3430	0.4541
YLD	Crop Yield	0.4838	0.3663	0.4769
PUP	Phosphorus Uptake	0.4571	0.3431	0.4543
NUP	Nitrogen Uptake	0.0667	0.0120	0.0672
SEDP	Sediment Bound Phosphorus	0.0681	0.0100	0.3842
SOLP	Soluble Phosphorus	0.1350	0.0087	0.1215
NSURQ	Nitrate in Surface Runoff	0.0532	0.0001	0.0715
NLATQ	Nitrate in Lateral Flow	0.5390	0.3529	0.4574
NTOTAL	Total Transported Nitrate	0.2106	0.1867	0.2503
PTOTAL	Total Transported Phosphorus	0.3369	0.2527	0.3272

**Table 29.** Adjusted R-Squared values for the model parameters of the ‘high’ fertilizer simulation series versus irrigation intensity showing three regression model comparisons.

<b>Variable:</b>	<b>Description:</b>	<b>Linear Reg. Adj. R-Sq.</b>	<b>Natural Log Transform Adj. R-Sq.</b>	<b>Square Root Transform Adj. R-Sq.</b>
IRR	Irrigation Volume	0.5544	0.3292	0.4608
W-STRS	Water Stress	0.5583	0.7560	0.6698
SW	Soil Water	0.2543	0.2039	0.2823
SURQ	Surface Runoff	0.2989	0.1983	0.2908
SYLD	Sediment Yield	0.0114	0.0229	0.0284
BIOM	Plant Biomass	0.3875	0.2867	0.3824
YLD	Crop Yield	0.4479	0.3299	0.4373
PUP	Phosphorus Uptake	0.3870	0.2867	0.3819
NUP	Nitrogen Uptake	0.2785	0.1716	0.2784
SEDP	Sediment Bound Phosphorus	0.1140	0.0486	0.1250
SOLP	Soluble Phosphorus	0.2446	0.0985	0.2472
NSURQ	Nitrate in Surface Runoff	0.1828	0.0588	0.1992
NLATQ	Nitrate in Lateral Flow	0.1164	0.0254	0.0819
NTOTAL	Total Transported Nitrate	0.0784	0.0210	0.0587
PTOTAL	Total Transported Phosphorus	0.1447	0.0642	0.1562

Tables 25 through 27 show that irrigation intensity is most predictive of the water stress level, as indicated by an adjusted R-squared value greater than 0.75, for both the high and low fertilizer levels and the combined data. A negative natural log transform function is seen to be most predictive of water stress levels, as water stress levels decrease dramatically with the application of irrigation, even at low irrigation intensity levels; however, water stress changes little as irrigation intensity increases at the higher irrigation intensity levels. This behavior most closely resembles the natural log transform function as indicated by the higher adjusted R-squared values.

The fact that strong R-squared values are not observed with other parameters indicates that the irrigation intensity level is not the exclusive or most predominant predictive factor involved in determining the parameter value measured. Nevertheless irrigation application is shown to have a statistically significant impact on each of these

parameters is indicated by the results of the  $t$ -test previously presented in Table 26. More predominant predictive factors are likely to include hydrological or meteorological parameters associated with each simulation.

## CHAPTER VI: CONCLUSIONS:

Based on the results obtained from the *IrrigEcon* application and the SWAT model a number of conclusions can be drawn. The conclusions listed below discuss general aspects of irrigation application in temperate zones, as well as the environmental impact of irrigation on nutrient and sediment transport processes.

1. It was found that the *IrrigEcon* application did distinguish between agricultural fields based on the potential net benefit associated with each field, given the range of site and meteorological conditions typical of Maryland's eastern shore. Net benefit calculations indicate that irrigation installations are more profitable for upland agricultural fields containing soils with higher sand content and higher hydraulic conductivity values. Agricultural fields associated with low lying areas, containing soils with higher silt and clay content values were less likely to profit from irrigation installations.
2. Based on the economic variables used in this analysis, the less expensive but less efficient center pivot system is recommended more frequently at lower water cost levels (less than 10 cents/m<sup>3</sup>). However, at higher water cost levels (greater than 10 cents/m<sup>3</sup>) the more expensive and more water efficient drip irrigation system emerges as the favored irrigation system particularly for upland agricultural fields characterized by soils with higher sand content and higher hydraulic conductivity.
3. Limitations of the net benefit modeling approach include the need for reliable and accurate economic data concerning the expected annual production

costs associated with each crop type, the expected price received by the farmer per unit yield, and an estimate of expected operational life and the installation and maintenance costs of irrigation systems evaluated.

The *IrrigEcon* application is also heavily dependent upon the SWAT output variables, particularly on crop yield values and actual/potential evapotranspiration values, which, if not accurately modeled, lead to erroneous results. To a lesser degree the *IrrigEcon* application depends upon the hydrologic variables and computational procedures used by SWAT that determine soil moisture conditions within a given agricultural field. SWAT is by design a soil and water assessment tool, and although it incorporates a plant/crop growth model needed in determining evapotranspiration values as well as the effects on sediment/nutrient transport processes, the primary strength and objective of SWAT is in modeling the hydrology of the system and predicting non-point source pollution processes. Considerable difficulty was found in modeling crop yield values to reflect values reported in the Maryland Agricultural Statistical Service annual reports.

4. From an environmental perspective, model analysis indicates that the use of irrigation can reduce the total quantity of nitrogen export from an agricultural field. However, phosphorus export did increase as did the total sediment yield. Sediment losses increased as a result of the higher average soil moisture content levels that resulted in higher runoff volumes. Increased sediment losses from agricultural fields accounted for an increased quantity of phosphorus being loss from agricultural fields due to sediment bound phosphorus concentrations.

## **CHAPTER VII: SUGGESTIONS FOR FURTHER STUDY:**

The *IrrigEcon* application developed in this project inherently assumes the use of a high quality freshwater source to serve as an irrigation input. However, in reality, agricultural production in water scarce regions of the world will of necessity have to take full advantage of recycled wastewater supplies and in some cases semi-brackish water to meet the demand, as freshwater sources are devoted to more valued domestic and industrial uses. It is expected that the lower quality waters could cause plant stress. The stress caused by the application of a lower quality water sources to agricultural fields may, potentially, negatively impact agricultural yields or require higher water application rates, which could potentially be incorporated into a model in order to determine optimal water use given the varied costs associated with available high quality and low quality water.

Such a model will aid policy makers in redefining quotas, which currently allocate freshwater supplies for each landowner. The rate of substitution of low quality water for high quality water will have to be made by policy makers based on the projected reduction in yields and the need to expand irrigation operations to meet yields obtained under high quality water conditions. If the effects of high and low quality waters could be studied and characterized on a variety of crop species, then such information could be used to optimize the allocation and distribution of limited water supplies. This information could be incorporated into a model, similar to the irrigation-economic model developed in this study, in order to determine the optimal equivalent quantities of lower grade waters given various price schemes.



One example of the need for such a model is seen in Israel where the incorporation of low quality water into the Israeli quota-system is currently a major problem faced by the Water Commission (Yaron, 1997). The adaptation of this irrigation economic model to evaluate the impact on yields with the use of low quality water will aid in this determination.

Secondly, the model does not account for salinity accumulation over the course of the growing season or years. Salinity can occur in areas of high irrigation when leaching requirements are insufficient to remove salts from the upper soil layers, even when higher quality sources are used. This is generally not a problem in temperate zones such as Maryland where there is high precipitation throughout the year. However, in arid regions heavily dependent on irrigation, salinity can become a problem, especially in cases where low irrigation water quality sources are utilized. A model designed to track salinity accumulation in the soil profile would require detailed information on water quality and initial soil concentrations as well as precipitation/leaching volumes, and ion adsorption within the soil matrix. Such a model would be able to prescribe irrigation events for the purpose of reducing salinity levels, given adequate information on the initial irrigation water quality.

Thirdly, future studies may wish to link a more realistic market-pricing model to the simplistic economic framework used in this study. The current model does not consider the effects of inflation on crop market price, irrigation installations or associated water costs, but rather assumes a constant cost throughout the simulation. The value of irrigation may be greater assuming that drought conditions will decrease the overall

supply of agricultural goods and thus increase the price of these goods during drought years.

Fourthly, the current model assumes that fertilizer inputs are supplied in sufficient quantities to produce maximum yields, and are not a limiting factor. SWAT is capable of monitoring phosphorus and nitrogen concentrations within the soil profile, and therefore the model presented here may be expanded to evaluate the effects of nitrogen and phosphorus levels, if deficit conditions exist, and the economic impact this may have on yield.

Finally, it has been suggested in this study that the increasing yields obtained through proper use of irrigation will also sustain high fertilizer use efficiency. The irrigation water supplied during periods of reduced or inadequate precipitation results in increased plant growth and an associated increase in nutrient utilization. The simple modeling done here indicates that irrigation results in less nitrogen export, but increase phosphorus transport due to sediment losses. However, further modeling and field validation will need to be conducted in order to verify or refute this claim, particularly given the expected variability in farm management practices. Field studies could allow for the determination of the full impact of supplemental irrigation on fertilizer utilization, and the potential reduction in fertilizer waste. Such a study could lend validity to the use of irrigation as a best management practice in the control and reduction of excess nutrients.

**APPENDICES:**

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## Appendix A: SWAT Model Methodology and Overview

The information provided gives an overview of the equations used by the model that are pertinent to the plant growth, meteorological and hydraulic components relevant to irrigation economic application. Secondly the information provides an indication of the input data required for model operation, outlined in the *Methods and Procedures* section of this document.

### *Hydrology:*

The fundamental component modeled by SWAT is the hydrologic cycle, which is separated into two major divisions: the land phase and the routing phase. The land phase is of principle importance in determining irrigation demand, and therefore will be the primary focus of the discussion below. The routing phase of the hydrological cycle is defined as the movement of water, sediments, nutrients and agricultural chemicals through the channel network (Neitsch et al., 2002a). The modeling of land phase hydrological processes in SWAT is based on a water balance approach synthesized in equation 31 (Neitsch, 2002b).

$$\theta_f = \theta_0 + \sum_{i=1}^t (P_i - Q_i - ET_i - DP_i - QR_i) \quad (31)$$

Where,  $\theta_f$  is the final soil-water content [mm],  $\theta_0$  is the initial soil-water content available for plant uptake on day  $i$ , defined as the initial soil-water content minus the permanent wilting point water content [mm],  $t$  is the time or model duration [days],  $P_i$  is the precipitation on day  $i$  [mm],  $Q_i$  is the surface runoff on day  $i$  [mm],  $ET_i$  is the

evapotranspiration on day  $i$  [mm],  $DP_i$  is the deep percolation, amount of water entering the vadose zone from the soil profile on day  $i$  [mm], and  $QR_i$  is the return flow on day  $i$  [mm].

The water balance equation used by SWAT evaluates the water entering and exiting each layer of the soil profile, and differs slightly from the water balance equation presented previously, which is concerned with the water entering and exiting the root zone as a whole over a given unit of time, and therefore has an added component that accounts for the growth of the plant root during the time interval under consideration. Moreover, the SWAT water balance equation does not specifically account for applied irrigation although this value can be incorporated into the model during model execution.

However, the SWAT water balance equation does incorporate a runoff component that is not accounted for in the previous water balance equation, which considers only the water infiltrating the soil surface. Each of the components of the soil-water balance equations is discussed separately in the paragraphs below.

*Evapotranspiration:*

Evapotranspiration ( $ET$ ) is the primary means by which water is lost from the soil profile and is a reflection of water consumption by the plants, and is therefore, of key importance in determining irrigation needs. Evapotranspiration is the combination of two simultaneous processes, water loss through direct evaporation from the soil surface, and transpiration from crops and plants (Allen et al., 1998). Evapotranspiration rates follow a diurnal oscillation fluctuating with net radiant energy, which must be replenished by precipitation, supplemental irrigation and upward swelling of groundwater supplies into the root zone. It is estimated that roughly 62% of all precipitation that falls over land

surfaces is reintroduced into the atmosphere through evapotranspiration (Dingman, 2002).

Evaporation is the process whereby liquid water is vaporized and removed from an evaporating surface, which include open bodies of water (rivers and lakes), as well as solid surfaces such as pavements, soils and wet vegetation. The vaporization of liquid water into gaseous form requires energy. Evaporation is, therefore, a reflection of the energy reaching the evaporating surface in the form of direct solar radiation and, to a lesser extent, ambient temperature. However, energy alone is insufficient to cause evaporation. The driving force behind this process is the vapor pressure gradient between the surface and the surrounding atmosphere (Allen et al., 1998). Therefore, the rate of evaporation is determined by the amount of moisture at the surface and the humidity or degree of saturation in the surrounding atmosphere. Wind accelerates this process by replacing the more saturated air nearest the evaporating surface with drier air, which has a greater capacity to absorb additional water. Evaporation is determined by using data on solar radiation, air temperature, humidity and wind speed.

Transpiration on the other hand is the process whereby water vapor contained within the intercellular spaces of the plant tissue is released through the stomatal aperture (Allen et al., 1998). As with evaporation, transpiration depends upon the energy supply, the vapor pressure gradient, and wind speed, but is also dependent on plant physiological characteristics. The rate at which water is absorbed by the plant depends upon the plant species, the stage of plant growth, and the accompanying soil and environmental conditions, which include nutrient availability, soil-water content, and salinity.

Nearly all water taken up by the plant is eventually lost to transpiration with very little remaining as net storage in the plant tissue (Miyazaki, 1993), and as such is the dominant process in the plant-water-soil relationship. It is estimated that of all the water absorbed by plants 95% or more is lost to transpiration with less than 5% used for metabolism and growth, thereby requiring several hundred grams of water to produce a single gram of dry plant matter (Kramer and Boyer, 1995).

The ratio between evaporation and transpiration is primarily determined by the fraction of solar energy reaching the soil surface versus the plant leaf tissue (Allen et al., 1998). However, as the processes occur simultaneously they are difficult to distinguish. Needless to say, water loss is primarily the result of transpiration once the ground cover vegetation is well established.

Due to the wide variability in plant diversity and characteristics it is often useful to look at evapotranspiration rates in relation to a reference evapotranspiration value ( $ET_0$ ). Historically, open water surfaces have been used as a reference surface. However, relating  $ET_0$  values to a specific crop has the advantage of incorporating biological and physical processes that are involved with evapotranspiration from plant surfaces. Differences in surface aerodynamics, vegetation control, and radiation characteristics present difficulties when comparing evapotranspiration measurements of vegetative fields to free water evaporation from evaporating pans.

These differences include the following. First, the albedo or reflectance of plant surfaces generally range from 0.2 to 0.25 whereas water surfaces can vary over a much wider range from 0.02 to 1.0. Secondly, the heat storage in soils differs from that of evaporation pans; pans can absorb and store energy and release it gradually thereby

allowing evaporation to continue to occur after the radiant energy source has set. Moreover, the resistance to air movement and exposure to climate differs, allowing moist air to be replaced more quickly with dry air over water surfaces than would normally occur over vegetative surfaces. And finally, the pan evaporation lags evapotranspiration on a diurnal basis and can also occur at night when compared to evapotranspiration values of vegetative surfaces (Burman and Pochop, 1994).

In order to eliminate these differences a standard lawn reference crop has been proposed by the Food and Agricultural Organization (FAO) for all climates and locations as a standardized reference point. To avoid problems of local calibration and the wide variation in grass species and morphology the proposed 'hypothetical' reference grass has a set of standardized, known characteristics that can be used in the evapotranspiration calculations. A hypothetical reference crop was selected in order to give a standard that could be applied to all locations despite differences in plant species compatibility or acclimation to a particular climate. Grass has been specifically selected, by the FAO, as the reference crop due to its worldwide acceptance and the comparatively copious amount of available data (Allen et al., 1998).

However, the problem remains of selecting the exact characteristics of the reference crop. The following unambiguous description of the hypothetical reference grass has come forth from a consultation of experts organized by the FAO in May of 1990, (Smith et al., 1992): "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 \text{ s m}^{-1}$  and an albedo of 0.23." The use of a hypothetical reference crop eliminates the need for site measurements, which may be difficult, time consuming and inaccurate. Moreover, it ensures that consistent parameters



are used, as opposed to measured parameters of a specific grass species, which may vary depending on site environmental conditions and the degree of climate acclimation to a particular location of the given grass species, thereby ensuring universal applicability.

SWAT deviates from this standard somewhat in that it uses a reference crop of alfalfa, standing 40 cm high with a minimum leaf resistance of 100 s/m (Neitsch et al., 2002a). The difference here is marginal, and alfalfa may in fact be more representative of typical crop species than a cut grass reference crop. However, as a consequence crop evapotranspiration coefficients, which relate actual evapotranspiration values to the predetermined reference evapotranspiration, must be determined in reference to alfalfa as opposed to the FAO developed reference grass crop.

The  $ET_0$  value gives an indication of the evaporating power of the atmosphere at a specific time and location. It represents the potential evapotranspiration of a well-watered reference crop. Once the reference evapotranspiration ( $ET_0$ ) has been calculated using the standardized parameters listed above in combination with local meteorological data, the potential evapotranspiration rates of a specific crop can be determined through the application of empirically derived crop coefficients that relate the evapotranspiration rate of the reference crop to the specific crop of interest.

Through the use of these predetermined empirical crop coefficients, independently measured for each plant species, the evapotranspiration rates of a wide variety of crops can be compared to one another through the reference  $ET_0$  intermediary. The water requirements of crop species can then be more easily determined when linked through this known climatic parameter. This two-step process avoids the difficulty of determining the physically based parameters required to calculate the evapotranspiration

values for each crop species directly, which are often unknown and difficult to measure, as will be discussed later in this section. Ideally, potential evapotranspiration rates for each crop species would be calculated directly if the physical properties of crops were known, such as albedo and surface resistance. However, as these values are difficult to determine and are not available for all species, an empirical two-step process is required.

*The Penman-Monteith Equation:*

Numerous methods have been proposed to calculate  $ET_0$ , the more commonly known methods include: the Blaney-Criddle, the radiation method, the modified Penman, and the pan evaporation method. SWAT itself provides three options for calculating potential evapotranspiration including: the Penman-Monteith method, the Priestley-Taylor method, and the Hargreaves method, each of which requires varying amounts of meteorological data (Neitsch et al., 2002a). However, the FAO has recommended the Penman-Monteith method (Allen et al., 1998), as a standard for widespread use in calculating evapotranspiration rates.

This recommendation is based largely on studies conducted by the Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE, 1990), and a parallel study commissioned by the European Community. These studies revealed largely varying results in the performance of over 20 methods in calculating  $ET_0$  values, varying widely with location and climatic conditions, revealing a great need for a standardize calculation procedure. The Penman-Monteith method was proposed to serve as this standardized method due to its strong performance in correctly predicting  $ET_0$  values in a wide range of locations and climates, and has provisions for situations in which there is a shortage of data (Allen et al., 1998). For these reasons the Penman-

Monteith method will be used in the SWAT model for calculating potential evapotranspiration. The following pages discuss its use and the variables required in its calculation.

The Penman-Monteith equation combines energy balance with mass transfer, and incorporates wind resistance parameters to account for the aerodynamic resistance ( $r_a$ ) caused by the upward air movement over the vegetation, and the surface/canopy resistance ( $r_s$ ) associated with the soil surface, leaf area, and the stomata opening. The Penman-Monteith equation is given as equation 32 (Allen et al., 1998).

The Penman-Monteith Equation may be presented as:

$$\lambda ET_0 = \frac{\Delta(R_n - G) + 86400 \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left( 1 + \frac{r_s}{r_a} \right)} \quad (32)$$

Where,  $\lambda ET_0$  is the vapor flux density [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $\lambda$  is the latent heat of vaporization [ $\text{MJ}/\text{kg}$ ],  $ET_{0r}$  is the reference evapotranspiration rate [ $\text{mm}/\text{day}$ ],  $R_n$  is the net radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $G$  is the soil heat flux [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $e_s$  is the saturation vapor pressure [ $\text{kPa}$ ],  $e_a$  is the actual vapor pressure [ $\text{kPa}$ ],  $(e_s - e_a)$  is the saturation vapor pressure deficit [ $\text{kPa}$ ],  $\rho_a$  is the density of air [ $\text{kg}/\text{m}^3$ ],  $c_p$  is the specific heat of the air,  $\Delta$  is the slope of the saturation vapor pressure temperature relationship [ $\text{kPa}/^\circ\text{C}$ ],  $\gamma$  is the psychrometric constant [ $\text{kPa}/^\circ\text{C}$ ],  $r_a$  is the aerodynamic resistance to vapor and heat diffusion [ $\text{s}/\text{m}$ ], and  $r_s$  is the bulk stomatal or canopy resistance [ $\text{s}/\text{m}$ ].

The soil heat flux ( $G$ ) used in the equation above can vary significantly over a period of a few hours, however the overall variation from day to day is small as the heat stored during the day is usually lost at night when the soil cools (ASCE, 1990). Therefore, the net magnitude of the daily heat flux is relatively small over a 10-30 day period (the time frame in which irrigation schedules will be considered), when the soil is under a crop cover. For this reason SWAT assumes a value of zero for the daily soil heat flux (Neitsch et al., 2002a).

The aerodynamic resistance ( $r_a$ ) used in the Penman-Monteith equation governs the transfer of heat and water vapor from the leaf surface to the air above the canopy. This value is determined using equation 33 (Allen et al., 1998).

$$r_a = \frac{\ln\left[\frac{z_m - d_h}{z_{om}}\right] \ln\left[\frac{z_h - d_h}{z_{oh}}\right]}{k^2 u_z} \quad (33)$$

Where,  $r_a$  is the aerodynamic resistance to vapor and heat diffusion [s/m],  $z_m$  is the height of wind measurements [m],  $z_h$  is the height of humidity measurements [m],  $d_h$  is the zero plane displacement height [m],  $z_{om}$  is the roughness length governing momentum transfer [m],  $z_{oh}$  is the roughness length governing transfer of heat and vapor [m],  $k$  is the von Karmans' constant for turbulent diffusion (0.41), and  $u_z$  is the wind speed at height  $z$  [m/s].

Values for the roughness lengths ( $z_{om}$  and  $z_{oh}$ ), and the zero plane displacement height ( $d$ ), used in the determination of aerodynamic resistance, are estimated using equations 34a, b, and c, respectively (Allen, 1988).

$$z_{om} = (0.123)h_c \quad (34a)$$

$$z_{oh} = (0.0123)h_c \quad (34b)$$

$$d = \frac{2}{3}h_c \quad (34c)$$

Where,  $d_h$  is the zero plane displacement height [m],  $z_{om}$  is the roughness length governing momentum transfer [m],  $z_{oh}$  is the roughness length governing transfer of heat and vapor [m],  $h_c$  is the mean height of vegetative canopy [m].

The transfer of vapor flow from the transpiring crop and evaporation from the soil surface is governed by the surface resistance ( $r_s$ ), which is given by equation 35 (Allen et al., 1989).

$$r_s = \frac{r_l}{(0.5)LAI} \quad (35)$$

Where,  $r_s$  is the bulk stomatal or canopy resistance [s/m],  $r_l$  is the average minimum daytime value of stomatal resistance for a well illuminated leaf [s/m], and  $LAI$  is the active or sunlit leaf area index [ $\text{m}^2$  (leaf area)/  $\text{m}^2$  (soil surface)].

The leaf area index ( $LAI$ ), used in the equation above, is defined as the upper side of the leaf area of a crop canopy per unit area of ground covered. Generally, for clipped lawn (12 cm in height) the active LAI ( $LAI_{active}$ ) can be estimated as half of the total LAI, as seen in the equation above. This is an assumption, which indicates that only half of the leaf area is contributing to the surface heat and vapor transfer. It is estimated that the

upper half of a dense canopy absorbs the majority of the available energy, while the lower half is shielded from the majority of the radiant energy that drives the process, and therefore, does not contribute significantly. Generally the value of LAI varies from 3-5 for mature crops (Allen et al., 1998), but varies with time, height and cultural practice. For clipped grass less than 0.15 m in height, LAI values can be approximated by equation 36, and can be estimated as equation 37 for tall grass hay and alfalfa (Allen et al., 1989).

$$LAI = 24h_c \quad \text{where, } h_c < 0.15 \text{ m} \quad (36)$$

$$LAI = 5.5 + 1.5 \cdot \ln(h_c) \quad \text{where, } h_c \geq 0.15 \text{ m} \quad (37)$$

Where,  $h_c$  is the mean crop height [m], and  $LAI$  is the leaf area index [ $\text{m}^2$  (leaf area)/  $\text{m}^2$  (soil surface)].

The stomatal resistance ( $r_l$ ) for well-watered grass and alfalfa canopies used in equation 35 is approximately 100 s/m (Allen et al., 1989). However, this approximation does not take into consideration the effects of temperature on stomatal resistance. The stomatal resistance varies with the crop species but is influenced by climate and water availability, increasing with decreasing soil-water availability. Some studies have shown that stomatal resistance can be influenced by radiation intensity, temperature and vapor pressure deficit (Allen et al., 1998).

It has been hypothesized that under well-watered conditions stomatal resistance is maintained at maximum levels until leaf temperatures increase to levels conducive to optimal enzymatic activity. Once these temperatures have been reached, the stomata

open to allow for evaporative cooling to maintain optimal temperature conditions (Hatfield et al., 1987). However, the biological response of stomata to environmental conditions is complicated and not fully understood, therefore a value of 100 s/m is used as an estimate of expected stomatal resistance for most crops.

Note that utilizing equation 35 for surface resistance ( $r_s$ ), and assuming a stomatal resistance of 100 s/m as recommended, and a crop height of 0.12 m (reference grass height) yields a surface resistance ( $r_s$ ) for the reference grass crop is 70 s/m. The equation has been found to work well for short crops such as lawns but is less accurate for taller crops such as corn and sorghum, where an additional resistance factor contributes to reducing evapotranspiration beyond stomatal surface resistance. Stockle and Kjelgaard (1996) recommend dividing the surface resistance component of the Penman-Monteith into two components: the first component for the surface resistance of the canopy ( $r_c$ ), and can again be calculated using equation 35 for surface resistance ( $r_s$ ); the second additional component accounts for resistance due to canopy structure ( $r_o$ ), which is a linear function of crop height given by equation 38.

$$r_o = bh_c \quad (38)$$

Where,  $r_o$  is the resistance due to canopy structure [s/m],  $h_c$  is the mean crop height [m], and  $b$  is an empirically determine regression coefficient [s/m<sup>2</sup>].

The calculation of surface resistance must be calibrated independently for each crop species being investigated. However, in the case of a short well-watered reference grass the canopy resistance calculated using equation 35 alone is sufficient.

Nevertheless, as mentioned previously, if sufficient data is available potential evapotranspiration rates can be calculated for each plant species directly without the use of a reference crop intermediary. However, due to the complexity of such determinations, the use of a reference crop intermediary is likely to continue to be a common practice into the foreseeable future (Allen et al., 1998).

Utilizing the above estimates of aerodynamic and surface resistance, the Penman-Monteith equation can be simplified to the following expression, shown as equation 39, for a reference lawn of 0.12 m in height with all measurements made 2 meters above ground level (Allen et al., 1989). Temperature measurements are made in degrees Kelvin.

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \gamma \left( \frac{5360}{T} - 4.02 \right) u (e_s - e_a)}{\Delta + \gamma(1 + 0.407u)} \quad (39)$$

Where,  $\lambda ET_0$  is the vapor flux density [MJ/m<sup>2</sup>·day],  $\lambda$  is the latent heat of vaporization [MJ/kg],  $ET_{0r}$  is the reference evapotranspiration rate [mm/day],  $R_n$  is the net radiation [MJ/m<sup>2</sup>·day],  $G$  is the soil heat flux [MJ/m<sup>2</sup>·day],  $e_s$  is the saturation vapor pressure [kPa],  $e_a$  is the actual vapor pressure [kPa],  $(e_s - e_a)$  is the vapor pressure deficit of the air [kPa],  $\rho_a$  is the density of air [kg/m<sup>3</sup>],  $c_p$  is the specific heat of the air,  $\Delta$  is the slope of the saturation vapor pressure temperature relationship [kPa/°C],  $\gamma$  is the psychrometric constant [kPa/°C],  $r_a$  is the aerodynamic resistance to vapor and heat diffusion [s/m],  $r_s$  is the bulk stomatal or canopy resistance [s/m], and  $T$  is the temperature [°K].



### *Meteorological Variables:*

The Penman-Monteith equation uses several meteorological values that must be calculated from readily available climatic data. Values needed for the calculation include: net radiation, soil heat flux, specific heat, saturation and actual vapor pressure, and the slope of the saturation vapor pressure-temperature relationship. These values have to be measured directly or estimated based on readily available meteorological data for the model location and specific site conditions. The paragraphs that follow discuss the determination of net radiation and other meteorological variables used in the Penman-Monteith equation.

Solar radiation is the largest energy source and is the primary factor controlling evapotranspiration rates when water is not a limiting factor (ASCE, 1990). It is, therefore, a critical factor to be determined when calculating potential evapotranspiration. The amount of radiation reaching any given point on the earth is a function of the time of the year, the time of the day, and the position's horizontal latitude (Allen et al., 1998). This is due to the constantly changing angle of incidence associated with the sun's radiation reaching the earth. Radiation striking a surface directly perpendicular to the sun's rays has a constant intensity of  $0.082 \text{ MJ/m}^2 \cdot \text{min}$ , and is referred to as the solar constant ( $G_{sc}$ ).

Extraterrestrial radiation is defined as the total short wave and long wave radiation above the atmosphere of the earth, before a portion of it is reflected or absorbed by cloud cover or atmospheric gases (ASCE, 1990). The extraterrestrial radiation ( $R_a$ ) is computed by equation 40 (Allen et al., 1998).

$$R_a = \left(24 \frac{60}{\pi}\right) G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (40)$$

Where,  $R_a$  is the extraterrestrial radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $G_{sc}$  is the solar constant [ $\text{MJ}/\text{m}^2 \cdot \text{min}$ ] ( $0.08202 \text{ MJ}/\text{m}^2 \cdot \text{min}$ ),  $d_r$  is the relative distance factor of the earth from the sun [dimensionless],  $\omega_s$  is the sunset hour angle [radians],  $\delta$  is the declination of the sun [radians], and  $\varphi$  is the latitude of the station [radians].

The equations used for calculating the declination of the sun ( $\delta$ ), the normalized relative distance of the earth from the sun ( $d_r$ ), and the sunset hour angle ( $\omega_s$ ) are included as in equations 41 a, b and c, respectively (Allen et al., 1989).

$$\delta = 0.4093 \sin(2\pi(284 + J) / 365) \quad (41a)$$

$$d_r = 1 + 0.033 \cos(2\pi J / 365) \quad (41b)$$

$$\omega_r = \arccos(-\tan(\varphi) \tan(\delta)) \quad (41c)$$

As the sun's radiation penetrates the earth's atmosphere a portion of the extraterrestrial radiation is scattered, reflected or absorbed by atmospheric clouds, gases, and dust (Allen et al., 1998). The amount of radiation reaching a horizontal plane on the earth's surface is referred to as solar radiation or shortwave radiation ( $R_s$ ). On a cloudless clear day the amount of radiation reaching the earth's surface is generally 75% of the extraterrestrial radiation ( $R_a$ ), and is referred to as the clear-sky solar radiation value ( $R_{so}$ ). The ratio of solar radiation to clear-sky solar radiation ( $R_s/R_{so}$ ) is an indication of the amount of cloud cover present on a given day. The net shortwave radiation is

determined as the net measured shortwave solar radiation minus reflectance, which is 23% for the hypothetical reference crop.

Another radiation source to be considered is that of terrestrial radiation or longwave radiation. Longwave radiation is an indication of the heat energy radiated by the earth into the atmosphere or lost to space (Allen et al., 1998). Longwave radiation can be received or emitted by the earth's surface, the net longwave radiation is, therefore, the difference between the outgoing and incoming longwave radiation.

Both long and shortwave radiation is considered when determining the net radiation ( $R_n$ ) value used in the Penman-Monteith equation. Net radiation is defined as the difference between the net incoming and outgoing radiation of both shortwave radiation and longwave or thermal radiation, as shown in equation 42a (Smith et al., 1992). The net longwave radiation is given as a negative value as its direction is considered from the earth to the atmosphere, the opposite direction of incoming solar radiation. The terms for the net shortwave and net longwave radiation are given by equations 17 b and c, respectively.

$$R_n = R_{ns} - R_{nl} \quad (42a)$$

$$R_{ns} = (1 - \alpha)R_s \quad (42b)$$

$$R_{nl} = \sigma \frac{(T_{\max K}^4 + T_{\min K}^4)}{2} \times (a_1 - 0.139\sqrt{e_d}) \left( a \frac{R_s}{R_{so}} + b \right) \quad (42c)$$

Where,  $R_n$  is the daily net radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $R_{ns}$  is the incoming net shortwave radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $R_{nl}$  is the outgoing net longwave radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $\alpha$  is the albedo (0.23 for hypothetical reference lawn) [dimensionless],  $R_s$  is the measured shortwave global radiation [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $R_{so}$  is the clear sky shortwave global radiation (i.e. no clouds) [ $\text{MJ}/\text{m}^2 \cdot \text{day}$ ],  $\sigma$  is the Stephan-Boltzman constant ( $4.903 \times 10^{-9}$   $\text{MJ}/\text{m}^2 \cdot \text{day} \cdot \text{K}$ ),  $T_{maxK}$  is the maximum daily air temperature [K],  $T_{minK}$  is the minimum daily air temperature [K],  $e_d$  is the vapor pressure at dew point [kPa], and  $a_1, a, b$  are empirical coefficients [dimensionless].

The value of the empirical coefficients used varies with cloud cover and vary with the ratio of measured solar radiation ( $R_s$ ) to clear-sky solar radiation ( $R_{so}$ ). The equations for the empirical coefficients are given as the set of equations 43 and 44 for the case of low cloud cover ( $R_s/R_{so} > 0.7$ ), and for the case of high cloud cover ( $R_s/R_{so} < 0.7$ ), respectively (Allen et al., 1989). The shortwave global radiation ( $R_s$ ) can be measured directly at agricultural meteorological stations through the use of various radiometers and pyranometers (Smith et al., 1992), or can be estimated from maximum and minimum temperatures, and extraterrestrial radiation (Allen et al., 1998).

In cases where there are few clouds ( $R_s/R_{so} > 0.7$ ):

$$a_1 = 0.26 + 0.1e - [0.0154(J - 180)]^2 \quad (43a)$$

$$a = 1.126 \quad (43b)$$

$$b = -0.07 \quad (43c)$$

Under cloudy conditions ( $R_s/R_{so} < 0.7$ ):

$$a_1 = 0.26 + 0.1e - [0.0154(J - 180)]^2 \quad (44a)$$

$$a = 1.0147 \quad (44b)$$

$$b = -0.06 \quad (44c)$$

Where,  $J$  is the day of the year (1-365) [integer], and  $a_1, a, b$  are empirical coefficients used in equation 42 [dimensionless].

The paragraphs and equations above discuss only the determination of net radiation, which is an indication of the energy available to contribute directly to evapotranspiration. However, the energy gained or lost by the soil during this process should be subtracted or added to the net radiation value as is done in the Penman-Monteith equation (Allen et al., 1998). This energy flow is referred to as the soil heat flux ( $G$ ), and is positive when soil is being heated (energy is being absorbed) and negative when soil is cooling (energy is being released). In most cases this value can be ignored, as the net soil heat flux is insignificant over the course of a day. Soil temperatures follow a diurnal cycle varying with daily temperatures with little net difference over short intervals. The soil heat flux ( $G$ ) is approximated by equation 45 (Smith et al., 1992).

$$G = \left( \frac{T_a - T_p}{\Delta t} \right) c_s \cdot d_s \quad (45)$$

Where,  $T_a$  is the average daily temperature [ $^{\circ}\text{C}$ ],  $T_p$  is the average daily temperature for past three days [ $^{\circ}\text{C}$ ],  $c_s$  is the general heat conductance for the soil surface [approx.  $0.38 \text{ MJ/m}^2 \cdot \text{day} \cdot ^{\circ}\text{C}$ ],  $ds$  is the estimated effective soil depth [m], and  $\Delta t$  is the time period [d].

Available energy is tied to the potential quantity of evapotranspiration through the latent heat of vaporization ( $\lambda$ ), which expresses the energy required to convert a unit mass of water from liquid to vapor (Allen et al., 1998). This variable is a function of temperature; at higher temperatures less additional energy is required, while at lower temperatures more energy is required. The latent heat of vaporization ( $\lambda$ ) is calculated using equation 46 (Allen et al., 1989). This value varies only slightly over normal temperatures, and therefore, can be assumed to be  $2.45 \text{ MJ/kg}$ , which corresponds to the latent heat for an air temperature of  $20^{\circ}\text{C}$  (Allen et al., 1998).

$$\lambda = 2.50 - (2.361 \times 10^{-3})T_a \quad (46)$$

Where,  $\lambda$  is the latent heat of vaporization [ $\text{MJ/kg}$ ], and  $T_a$  is the average daily temperature [ $^{\circ}\text{C}$ ].

Another meteorological concept, significant in the determination of evapotranspiration, is air humidity. The energy equations discussed above provide the means by which water is converted to vapor form; however, the driving force behind this process is the vapor pressure gradient between the plant surface and the surrounding atmosphere.

Vapor pressure, dewpoint temperature and relative humidity are all common expressions of the water content of the air (Allen et al., 1998). Vapor pressure is a measure of the partial pressure exerted by the water vapor in the air that contributes to the total atmospheric pressure. Vapor pressure is directly related to the water content of the air, the capacity of which is a function of temperature. At higher temperatures air can hold a greater quantity of water vapor, and has less capacity at lower temperatures. The partial pressure of the water vapor when the air is fully saturated at a given temperature is referred to as the saturation vapor pressure ( $e_s$ ).

The slope of the plot of saturation vapor pressure versus temperature ( $\Delta$ ) is small at lower temperatures, but increases exponentially at higher temperatures (Allen et al., 1998). It is, therefore, used as a parameter to describe vaporization, and is used in the Penman-Monteith equation. The slope of the saturation vapor pressure curve is given by equation 47 (Smith et al., 1992).

$$\Delta = \frac{4098e_s}{(T + 237.3)^2} \quad (47)$$

Where,  $e_s$  is the saturation vapor pressure [kPa],  $T$  is the temperature [ $^{\circ}$ C], and  $\Delta$  is the slope of the saturation vapor pressure function [kPa/ $^{\circ}$ C].

The saturation vapor pressure for a given temperature is determined by equation 48 (Allen et al., 1998). Due to the non-linearity of temperatures over the course of a day, a week or a month, saturation vapor pressure is usually determined as the average of the saturation vapor temperature associated with the maximum and minimum temperature for a given time period.

$$e_s = 0.6108 \exp \left[ \frac{17.27T}{T + 237.3} \right] \quad (48)$$

Where,  $e_s$  is the saturation vapor pressure [kPa] and  $T$  is the temperature [ $^{\circ}\text{C}$ ].

The actual vapor pressure ( $e_a$ ) reflects the vapor pressure of the actual quantity of water vapor in the air. The actual vapor pressure is always less than or equal to the saturation vapor pressure. The actual vapor pressure value can be calculated in a number of ways using dewpoint temperature, relative humidity or psychrometric data. Equation 49 uses dewpoint temperature to calculate the actual vapor pressure (Allen et al., 1998). Dewpoint temperature is the temperature to which air needs to be cooled in order to reach saturation.

$$e_a = 0.6108 \exp \left[ \frac{17.27T_{dew}}{T_{dew} + 237.3} \right] \quad (49)$$

Where,  $e_s$  is the saturation vapor pressure [kPa] and  $T_{dew}$  is the dewpoint temperature [ $^{\circ}\text{C}$ ].

The difference between the saturation and actual vapor pressure ( $e_s - e_a$ ), used in the Penman-Monteith equation, is referred to as the vapor pressure deficit and is an indication of the evaporative capacity of the air. The Penman-Monteith equation also utilizes the psychrometric constant ( $\gamma$ ) and the density of air ( $\rho_a$ ). The psychrometric constant is determined by equation 50 and the density of air is given by equation 51 (Allen et al., 1998):



$$\gamma = \frac{c_p P_a}{\varepsilon \lambda} \quad (50)$$

Where,  $c_p$  is the specific heat of moist air at constant pressure [MJ/kg·°C] ( $1.01 \times 10^{-3}$  MJ/kg·°C),  $P_a$  is the atmospheric pressure [kPa],  $\varepsilon$  is the ratio of molecular weights of air to water (0.622), and  $\lambda$  is the latent heat of vaporization [MJ/kg].

$$\rho_a = \frac{1000 P_a}{T'_v R} \quad (51)$$

Where,  $\rho_a$  is the atmospheric density [kg/m<sup>3</sup>],  $R$  is the specific gas constant [286.9 J/kg·K],  $P_a$  is the atmospheric pressure [kPa], and  $T'_v$  is the virtual temperature [K].

Both of the equations above use atmospheric pressure. Data on atmospheric pressure, together with air density, may be available from meteorological stations, or can be calculated using the ideal gas law assuming a constant temperature laps rate, and the virtual temperature ( $T'_v$ ), which represents the temperature of a dry air parcel with heat content equivalent to a similar moist parcel. The atmospheric pressure and the vertical temperature are represented by equations 52 and 53, respectively (Allen et al., 1998). Generally, it is appropriate to set the values for  $P_0$ ,  $T_0$ , and  $z_0$ , used in the calculation of atmospheric pressure below, to the values used for standard atmosphere at sea level, which are 101.3 kPa, 293 K, and 0 m, respectively.

$$P = P_0 \left[ \frac{T_0 - \alpha(z - z_0)}{T_0} \right]^{g/(\alpha R)} \quad (52)$$

$$T'_v = \frac{T}{1 - 0.378 \frac{e_d}{P}} \quad (53)$$

Where,  $T'_v$  is the virtual temperature [K],  $P$  is the atmospheric pressure estimate at elevation [kPa],  $T$  is the temperature [K],  $R$  is the specific gas constant [286.9 J/kg·K],  $P_0$  is the known atmospheric pressure [kPa],  $T_0$  is the absolute temperature [K],  $z_0$  is the elevation at reference [m],  $z$  is the elevation [m],  $\alpha$  is the assumed constant adiabatic lapse rate [K/m],<sup>29</sup>  $e_d$  is the vapor pressure at dew point [kPa], and  $g$  is the gravitational constant [9.81 m/s<sup>2</sup>].

*Precipitation and Weather Data Generation:*

The primary source of water into the soil profile, with the exception of periodic supplemental irrigation, is precipitation. As stated above actual precipitation values can be entered directly or can be generated during the simulation based on historical climatic data supplied for a given watershed. For simulated data the SWAT weather generator uses a model developed by Nicks (1974), and defines a day as either wet or dry using a first order Markov chain model that compares a randomly generated number to the monthly wet-dry probabilities supplied by the user (Neitsch et al., 2002a). The intensity of the rainfall event is determined from a skewed distribution or modified exponential distribution.

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<sup>29</sup> Approximately 0.0065 K/m for saturated air or 0.01 K/m for dry air (Allen et al., 1989). The equation for atmospheric pressure is relatively insensitive to  $\alpha$  values for elevations between 0-7000 m.

Other climatic variables generated by SWAT based on input data include: air temperature and solar radiation, wind speed and relative humidity. Daily temperatures and solar radiation are determined from a normal distribution of supplied values and are adjusted upward or downward depending on if the day is simulated as a dry or wet day. Daily humidity values are likewise adjusted for dry and wet days based on monthly averages. The determination of these climatic variables are critical not only because of their importance in determining precipitation, but also because of the important role they play in determining the evapotranspiration component of the water balance equation, as well as in determining infiltration rates in the case of freezing temperatures (Nietsch et al., 2002a).

*Runoff Calculation:*

When the precipitation or irrigation application rate exceeds the infiltration rate surface runoff will commence once all surface depressions have been filled. SWAT provides a choice of two methods for calculating surface runoff: the SCS (USDA Soil Conservation Service) curve number method, and the Green and Ampt method (Neitsch et al., 2002a). The SCS runoff curve number method uses equation 54 in order to calculate the runoff component ( $Q$ ) (Borah and Bera, 2003), and is the method used in this study. Runoff is calculated by SWAT only when precipitation exceeds the infiltration rate.

$$Q = \frac{(R_{day} - I_a)^2}{R_{day} - I_a + S_r} \quad (54)$$

Where,  $Q$  is the direct runoff [mm],  $R_{day}$  is the accumulated rainfall [mm],  $S_r$  is the potential difference between rainfall and direct runoff [mm], and  $I_a$  is the initial abstraction [mm].

The initial abstraction variable ( $I_a$ ), which accounts for surface storage, interception, and infiltration prior to runoff, can be approximated as  $0.2S_r$  and substituted into the equation above. The variable  $S_r$  represents the potential difference between rainfall and direct runoff and can be determined using equation 55.

$$S_r = \frac{25400}{CN} - 254 \quad (55)$$

Where,  $S_r$  is the potential difference between rainfall and direct runoff [mm], and  $CN$  is the curve number representing runoff potential for a soil cover complex (values 2 to 100).

The curve number used by SWAT in the equation above is a function of soil permeability, land use and antecedent soil-water conditions, and is obtained from the SCS Engineering Division (Neitsch, 2002b). SCS curve numbers used for agricultural and urban lands are included in Appendix B of this report for various land use, management practices, hydrologic conditions and soil group combinations. Peak runoff ( $q_p$ ), given by equation 56, is calculated in order to determine erosion energy for the basin area used in the universal soil loss equation described later in this text.

$$q_p = \frac{C \cdot i \cdot A}{3.6} \quad (56)$$

Where,  $q_p$  is the peak runoff rate (values 0.02 to 0.95),  $i$  is the rainfall intensity [mm/hr],  $A$  is the area of subbasin [ha], and  $C$  is the runoff coefficient [dimensionless]. The runoff coefficient ( $C$ ) used in the equation above is the ratio of inflow rate ( $i \cdot A$ ) to the peak discharge rate ( $q_p$ ), and is calculated using equation 57 (Neitsch et al., 2002a).

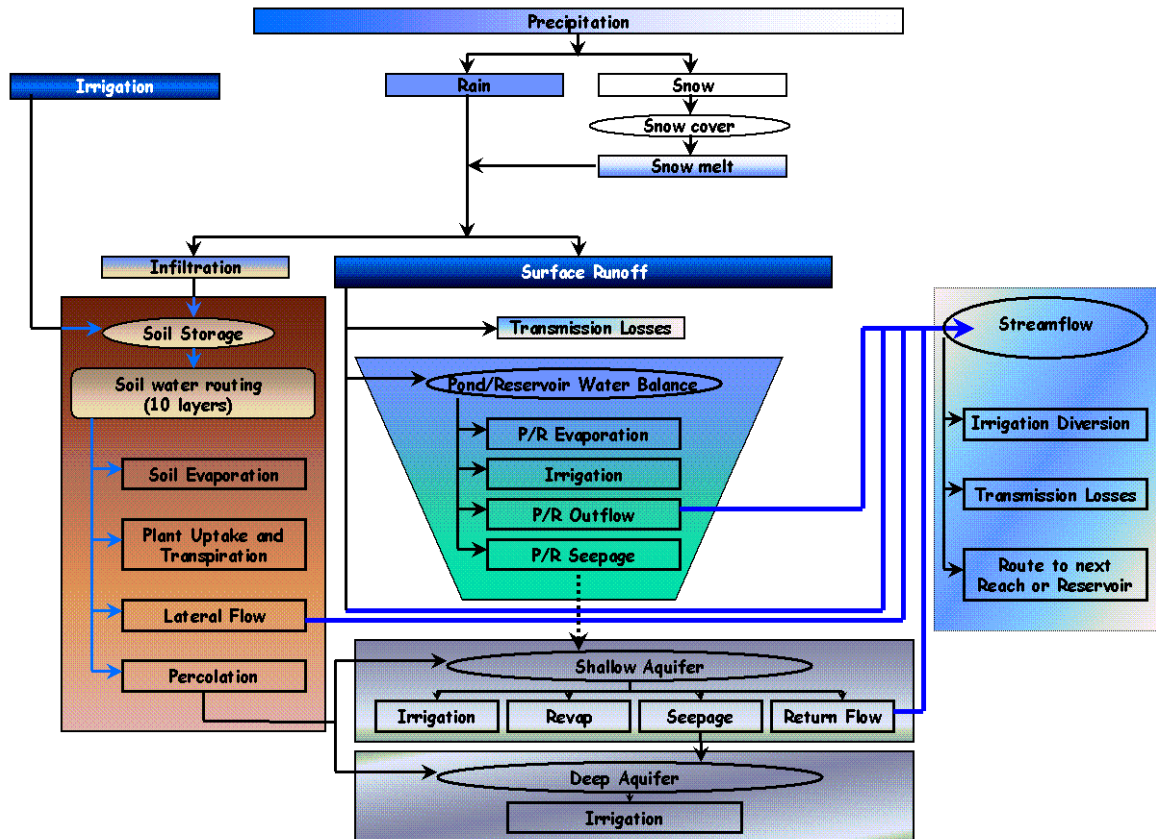
$$C = \frac{Q_{surf}}{R_{day}} \quad (57)$$

Where,  $Q_{surf}$  is the surface runoff [mm],  $R_{day}$  is the accumulated rainfall [mm], and  $C$  is the runoff coefficient [dimensionless].

Runoff contributes to the total overland flow, which eventually finds its way into rivers, tributaries, reservoirs and catchments, where the water may be diverted for other purposes or seep into the groundwater supply. Only the water that enters the soil profile contributes to the total soil-water content, and is accessible by the plants. However, surface runoff is an important component of the hydrologic cycle in the watershed, therefore, it remains an important parameter in this study. As an alternative to the SCS curve number method, SWAT provides the option of using the Green and Ampt infiltration method, however, this method requires breakpoint precipitation data that is often too difficult to obtain (Neitsch et al., 2002a), and therefore is not used in this study.

The amount of water entering the soil profile is taken as the difference between the precipitation or applied irrigation and surface runoff. Once water has entered a given

soil layer it exits as a result of percolation or seepage, subsurface lateral flow, plant uptake, or return flow from groundwater to surface streams. The multiple potential pathways of water movement simulated by SWAT are graphically illustrated in Figure 44. The figure shows that all water entering the system in the form of precipitation or irrigation is diverted initially into runoff or infiltration. The figure also lists the multiple pathways in which water might be transferred from one storage area or layer to the next, including: percolation or seepage, subsurface lateral flow, plant uptake, and return flow from groundwater to surface streams.



**Figure 44.** Schematic of pathways available for water movement in SWAT.<sup>30</sup>

*Percolation Calculation in SWAT:*

Percolation is calculated using a storage routing methodology, which assumes that water is evenly distributed within a given layer, but varies between layers. This simplifies the calculation by eliminating the need to model horizontal unsaturated flow as a result of gradients between adjacent areas of high and low water content (Neitsch et al., 2002a). This is an important consideration when modeling the effects of irrigation application methodologies with varying uniformity or distribution coefficients. The

<sup>30</sup> Figure obtained from Blackland Research and Extension Center. Available WWW: [http://www.brc.tamus.edu/swat/newmanual/intro/overview\\_land.html](http://www.brc.tamus.edu/swat/newmanual/intro/overview_land.html)

equation used to model water movement from one layer to the next is given by equation 58 as (Neitsch et al., 2002a);

$$w_{perc,ly} = \theta_{ly,excess} \cdot \left( 1 - \exp \left[ \frac{-\Delta t_s}{TT_{perc}} \right] \right) \quad (58)$$

Where,  $w_{perc,ly}$  is the amount of water percolating to the underlying soil layer [mm of water],  $\theta_{ly,excess}$  is the drainable volume of water on a given day [mm of water],  $\Delta t_s$  is the length of time step [hr], and  $TT_{perc}$  is the travel time for percolation [hr].

The travel time ( $TT_{perc}$ ) for percolation varies with each soil layer based on the hydraulic conductivity and the amount of water in the soil layer when fully saturated. The determination of the travel time is given by equation 59 as (Neitsch et al., 2002a);

$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}} \quad (59)$$

Where,  $SAT_{ly}$  is the amount of water in the soil layer when saturated [mm H<sub>2</sub>O],  $FC_{ly}$  is the water content of the soil layer at field capacity [mm H<sub>2</sub>O],  $K_{sat}$  is the saturated hydraulic conductivity [mm/h], and  $TT_{perc}$  is the travel time for percolation [hr].

Note that SWAT only models percolation in the case where the soil-water content exceeds the field capacity of the soil (Neitsch et al. 2002a). In this case the drainable volume of water on a given day ( $\theta_{ly,excess}$ ), used in equation 59, is the difference between the soil-water content at saturation for that layer and the soil-water content for that layer



at field capacity. When the soil-water content is less than field capacity the drainable water volume is zero and no percolation occurs.

Field capacity is defined as the soil-water content after a thoroughly wetted soil has been allowed to drain for two days. For the purposes of modeling field capacity in SWAT, field capacity has been redefined in terms of tension, and refers to the amount of water held in the soil at a tension of 1/3 bar (0.033 MPa) (Neitsch et al. 2002a). The permanent wilting point has been redefined in SWAT as the soil-water content held at a tension of 15 bar (1.5 MPa). The plant available water content, as defined in SWAT, is the difference between the soil water content at field capacity and the wilting point. Values for field capacity, wilting point, and plant available water, vary with the soil porosity, pore size and surface interaction between soil particles and the water. Table 30 lists water content values for three textured sands varying with clay content.

**Table 30.** Water content for various texture soils at different moisture conditions (Neitsch et al. 2002a).

Texture	Clay Content (% Solids)	Water Content (fraction total soil volume)			
		Saturation	Field Capacity (FC)	Wilting Point (WP)	Plant Available Water (AWC)
Sand	3 %	0.40	0.06	0.02	0.04
Loam	22 %	0.50	0.29	0.05	0.24
Clay	47 %	0.60	0.41	0.20	0.21

SWAT uses equation 60 to estimate the volumetric water content at permanent wilting point for each soil layer (Neitsch et al. 2002a). The bulk density ( $\rho_b$ ) used in the equation below is defined as the mass of solids over the total volume; bulk density reflects the relative amount of pore space in the soil matrix, as seen in equation 62.

$$WP_{ly} = 0.40 \frac{m_c \cdot \rho_{b,ly}}{100} \quad (60)$$

Where,  $WP_{ly}$  is the water content at wilting point for the layer [mm/mm],  $m_c$  is the percent clay content [%],  $\rho_{b,ly}$  is the bulk density for soil layer [Mg/m<sup>3</sup>]. Water available content values must be determined by SWAT for each HRU.

*Lateral Flow Calculations in SWAT:*

Lateral flow is significant for sloped or hilly areas with soils having high hydraulic conductivity and a shallow impermeable or semi-permeable layer (Neitsch et al. 2002a). Lateral flow is an important parameter in determine irrigation schedules for fields on hilly or sloped areas, and may result in very different irrigation schedules within the same region based on the slope and elevation of the field. Moreover, lateral flow has direct bearing on the soil-water content of the adjacent fields, thereby potentially having an effect on the irrigation demand of adjacent fields.

As with the calculation of percolation, SWAT models the lateral outflow of a given hill segment whenever the water content of the soil exceeds the field capacity of the soil for that segment. In the case where the water content for the soil is less than field capacity, the drainable volume is zero, resulting in no lateral flow. For a sloped area the drainable volume of water stored in the saturated zone is given by equation 61 as;

$$SW_{ly,excess} = \frac{1000 \cdot H_0 \phi_d \cdot L_{hill}}{2} \quad (61)$$

Where,  $SW_{ly}$  is the drainable volume of water [mm H<sub>2</sub>O],  $H_0$  is the saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness [mm/mm],  $\phi_d$  is the drainable porosity of the soil [mm/mm], and  $L_{hill}$  is the hillslope length [m].

The drainable porosity of the soil layer ( $\phi_d$ ) used in the equation above is calculated as the difference between the total soil layer porosity ( $\phi_{total}$ ) and the soil porosity at field capacity ( $\phi_{fc}$ ). The total soil porosity depends upon the soil bulk density and soil particle density, and is given by equation 62 (Neitsch et al., 2002a).

$$\phi_{total} = 1 - \frac{\rho_b}{\rho_s} \quad (62)$$

Where,  $\phi_{total}$  is the total soil layer porosity [mm/mm],  $\rho_b$  is the bulk density [Mg/m<sup>3</sup>], and  $\rho_s$  is the particle density [Mg/m<sup>3</sup>].<sup>31</sup>

The total volume of water being drained from the hill segment is estimated by equation 38 (Neitsch et al., 2002a).

$$Q_{lat} = 0.024 \cdot \left( \frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}} \right) \quad (63)$$

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<sup>31</sup> A default value of 2.65 Mg/m<sup>3</sup> is used in SWAT (Neitsch et al., 2002a).

Where,  $Q_{lat}$  is the volume of water being drained from the hill segment [ $m^3$ ],  $SW_{ly,excess}$  is the drainable volume of water [ $mm\ H_2O$ ],  $K_{sat}$  is the saturated hydraulic conductivity [ $mm/h$ ],  $slp$  is the slope input, increase in elevation per unit distance [ $m/m$ ],  $\phi_d$  is the drainable porosity of the soil [ $mm/mm$ ], and  $L_{hill}$  is the hillslope length [ $m$ ].

The discussion above involves the various mechanisms by which water is added to or removed from the soil layers within SWAT. Water is supplied primarily through precipitation, and enters or exits a unit volume as a result of runoff, evapotranspiration, percolation and lateral flow. This simple mass balance approach provides the framework for determining irrigation schedules.

Nevertheless, the full capability of SWAT goes far beyond this, much of which is not relevant to the irrigation economic application developed in this study. Because of the complexity of water distribution in the environment, SWAT, of a necessity, incorporates a number of component models that interact with one another in order to present the comprehensive whole. The processes modeled by SWAT include the movement of water to and from shallow and deep aquifers, the movement of water through channel streams, and the transport of non-point source pollutants including sediment, nitrogen and phosphorus fertilizers and agro-chemicals. However, as irrigation application is primarily concerned with the available water within the root zone of the plants, only a brief introduction will be presented here concerning the remaining capabilities of the SWAT model.

#### *Crop Growth/Land Cover:*

One notable exception to this is the growth model incorporated into SWAT, which is of critical importance in determining the depth of the root zone, the

evapotranspiration potential and the crop yield. SWAT uses a single plant growth model, a simplification of the EPIC model, to simulate land covers (Neitsch et al., 2002a). SWAT calculates the ideal biomass conversion given climatic conditions as a function of the intercepted energy and the plant's efficiency in converting energy to biomass. Heat units are used to determine the rate of growth and are calculated as the difference between the average daily temperature and the base growth temperature. Growth and subsequent biomass production occurs on those days in which this value is positive. Plant growth then determines water and nutrient uptake from the soil profile, which is reflected in a parallel decrease in the soil-water content and nutrient content of the soil layers within the root zone.

The heat unit theory, upon which plant growth is modeled in SWAT, theorizes that plants have heat requirements for growth to occur, which must be quantified and linked to a time to maturity (Neitsch et al., 2002a). This theory postulates that temperature is the most important factor governing plant growth, and that a minimum or base temperature must be reached before plant growth can occur. This base temperature, which triggers growth, varies from species to species, and therefore must be entered as input data into the model.

Based on this theory only the portion of the daily temperature that exceeds this base temperature will contribute to plant growth (Neitsch et al., 2002a). Each degree of the mean daily temperature that exceeds the base temperature is referred to as one heat unit. By knowing the planting date, the base temperature and mean daily temperatures for each day of the growing season, the total number of days required to bring a crop to

maturity can be calculated. The total number of heat units is calculated as the sum of all heat units from the planting date to plant maturity.

By taking this approach, specific stages in the growth cycle of the plant can be associated with a set of accumulated number of heat units. Therefore, modeling plant growth stages, such as vegetative cover, flowering, and maturity, can be determined by keeping track of the accumulated temperature values. However, it should be noted that if the mean daily temperature exceeds a certain threshold, the excessive temperature might contribute negatively to plant growth.

This method of monitoring plant growth is particularly useful in SWAT, and allows the user to schedule events and management operations based on accumulated heat units, or the fraction of the total growth cycle. To schedule events outside of the growing season of the specific crop, SWAT keeps track of another heat index that is based solely on the heat units in excess of 0 °C, referred to as the base zero index (Neitsch et al., 2002a).

Plant growth is modeled by simulating leaf area development, light interception and conversion of intercepted light into biomass varying with the plant species radiation-use efficiency (*RUE*) (Neitsch et al., 2002a). Biomass production on a given day is determined by the product of the radiation-use efficiency for the plant species and the amount of intercepted photosynthetically active radiation on a given day, as shown in equation 64. The radiation-use efficiency value, also referred to as the biomass-energy ratio, is plant species specific, and is defined in the plant growth database for each crop/land cover.

$$\Delta bio = RUE \cdot H_{phosyn} \quad (64)$$

Where,  $\Delta bio$  is the potential increase in plant biomass on a given day [kg/ha],  $H_{phosyn}$  is the intercepted photosynthetically active radiation [MJ/m<sup>2</sup>], and  $RUE$  is the radiation-use efficiency [(kg/ha)/(MJ/m<sup>2</sup>)]. Radiation use values associated with the four crop species included in this study are listed below:

<u>Crop</u>	<u>RUE Value</u>
Corn	39.0
Wheat	35.0
Soybean	25.0
Sorghum	33.5

The amount of intercepted photosynthetically active radiation, used in this equation, is given by equation 65 as;

$$H_{phosyn} = 0.5 \cdot H_{day} \cdot (1 - \exp(k_l \cdot LAI)) \quad (65)$$

Where,  $H_{day}$  is the incident total solar radiation [MJ/m<sup>2</sup>],  $H_{phosyn}$  is the intercepted photosynthetically active radiation [MJ/m<sup>2</sup>],  $k_l$  is the light extinction coefficient<sup>32</sup>, and  $LAI$  is the leaf area index.

Using these equations, the total biomass on any given day is calculated as the sum of biomass production for all days since seeding. The radiation-use efficiency value used in the equation above varies with each species, but is also sensitive to CO<sub>2</sub> concentrations (Neitsch et al., 2002a), which are on the rise as a result of global climate change.

However, in order to simplify the required input parameters it is assumed that radiation-

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<sup>32</sup> SWAT uses a light extinction coefficient value of -0.65 for all plants (Neitsch et al., 2002a).

use efficiency values will remain constant for a given plant species for a constant mean CO<sub>2</sub> concentration.

Aside from biomass production, two important remaining growth characteristics are canopy cover or height, needed in the determination of evapotranspiration rates, and root development, needed in the determination of the depth of the root zone for calculation of available water. Canopy height is a function of the plants maximum leaf area index corresponding to a given fraction of potential heat units ( $fr_{LAImx}$ ), as determined by equation 66. The fraction of potential heat units used in this calculation is determined by equation 67 (Neitsch et al., 2002a).

$$h_c = h_{c,max} \cdot \sqrt{fr_{LAImx}} \quad (66)$$

Where,  $h_c$  is the canopy height for a given day [m],  $h_{c,max}$  is the plant's maximum canopy height [m], and  $fr_{LAImx}$  is the fraction of the plant's maximum leaf are index corresponding to a given fraction of potential heat units, given by equation 67 [dimensionless].

$$fr_{LAImx} = \frac{fr_{PHU}}{fr_{PHU} + \exp(l_1 - l_2 \cdot fr_{PHU})} \quad (67)$$

Where,  $fr_{PHU}$  is the fraction of potential heat units accumulated for the plant on a given day in the growing season [dimensionless] and  $l_1$ ,  $l_2$  is the shape coefficients [dimensionless].



The equations for the fraction of potential heat units accumulated and the shape coefficients ( $l_1$  and  $l_2$ ) used in the equation above are given by equations 68-70 as;

$$fr_{PHU} = \frac{\sum_{i=1}^d HU_i}{PHU} \quad (68)$$

Where,  $d$  is the day of the growing season [day],  $HU$  is the heat units accumulated on day  $i$  [heat units], and  $PHU$  is the total potential heat units for the plant [heat units]

$$l_1 = \ln \left[ \frac{fr_{PHU,1}}{fr_{LAI,1}} - fr_{PHU,1} \right] + l_s \cdot fr_{PHU,1} \quad (69)$$

$$l_2 = \frac{\left( \ln \left[ \frac{fr_{PHU,1}}{fr_{LAI,1}} - fr_{PHU,1} \right] - \ln \left[ \frac{fr_{PHU,2}}{fr_{LAI,2}} - fr_{PHU,2} \right] \right)}{fr_{PHU,2} - fr_{PHU,1}} \quad (70)$$

Where,  $fr_{PHU,1}$  is the fraction of the growing season corresponding to the 1<sup>st</sup> point on the optimal leaf area development curve [dimensionless],  $fr_{LAI,1}$  is the fraction of the maximum plant leaf are index corresponding to the 1<sup>st</sup> point on the optimal leaf area development curve [dimensionless],  $fr_{PHU,2}$  is the fraction of the growing season corresponding to the 2<sup>nd</sup> point on the optimal leaf area development curve [dimensionless], and  $fr_{LAI,2}$  is the fraction of the maximum plant leaf are index corresponding to the 2<sup>nd</sup> point on the optimal leaf area development curve [dimensionless].

Root development varies with canopy growth in that the plants devote more energy, proportionally, to root development during the initial stages than to above ground biomass. During the initial stages of plant growth roots comprise up to 50% of the initial biomass, which falls to as little as 5% of the total biomass for a mature plant (Neitsch et al., 2002a). As a general rule, root depth increases 1-1 ½ feet per month of plant growth, until the full root depth is achieved as determined by the crop genetics and environmental conditions. Plants requiring two months to maturity obtain root depths of 2-3 feet; plants requiring three to four months to maturity extend roots to 3-5 feet; while plants requiring six months grow to 6-10 feet deep (Israel and Hansen, 1962). As a result, the amount of water accessible to the plant in the root zone varies greatly with the plants growth stage.

Therefore, proper irrigation scheduling requires an estimate of the effective rooting depth. The increase in rooting depth can be approximated by the following linear interpolation (ASCE, 1990) shown in equation 71a and b below. Once the crop approaches its maximum root depth at the date of effective full cover, it is assumed that the rooting depth will remain constant for the remainder of the growth cycle.

$$R_z = R_{z_i} + \frac{D - D_p}{D_c - D_p} (R_{z_{\max}} - R_{z_i}) \quad D < D_c \quad (71a)$$

$$R_z = R_{z_{\max}} \quad D < D_c \quad (71b)$$

Where,  $R_{z_i}$  is the initial effective rooting depth at planting or plant emergence [m]<sup>33</sup>,  $R_{z_{max}}$  is the maximum effective rooting depth for a mature crop [m]<sup>34</sup>,  $D$  is the current calendar day of the year [day],  $D_p$  is the planting date [day], and  $D_c$  is the date of effective full cover [day].

SWAT assumes that annuals achieve full root depth once 40% of the annual potential heat units (i.e.  $fr_{PHU} = 0.40$ ) have been achieved. For annuals SWAT assumes that the root depth increases linearly up to a maximum depth as indicated by equation 72a (Neitsch et al., 2002a). Once the threshold of the accumulated heat units is achieved, it is assumed that root depth remains at a constant maximum depth (equation 72b). Perennials and trees are assumed to be at full coverage at all times during the simulation, and are, therefore, assumed to be at a constant maximum root depth.

$$z_{root} = 2.5 \cdot fr_{PHU} \cdot z_{root, mx} ; \quad \text{if: } fr_{PHU} \leq 0.40 \quad (72a)$$

$$z_{root} = z_{root, mx} ; \quad \text{if: } fr_{PHU} > 0.40 \quad (72b)$$

Where,  $z_{root}$  is the root development in the soil on a given day [mm],  $z_{root, mx}$  is the maximum depth for root development in the soil [mm], and  $fr_{PHU}$  is the fraction of potential heat units accumulated for the plant on a given day in the growing season [dimensionless].

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<sup>33</sup> Generally assumed to range from 4-10 cm (ASCE, 1990)

<sup>34</sup> Full list of maximum effective rooting depths can be obtained from Table 2.7 of *ASCE Manuals and Reports on Engineering Practice No. 70* (ASCE, 1990).

It should be noted that achieving a maximum rooting depth assumes ideal growing conditions. Rooting depth can be limited by the existence of crusted layers or subsurface compaction (Shaxson and Barber, 2003), thereby preventing full root development. Information regarding compacted soil layers that prevent full root development is contained within soils data available online as will be discussed later in this text.

In SWAT the root fraction of the total biomass is assumed to be 40% of the biomass at emergence and 20% of the biomass at maturity, as given by equation 73 (Neitsch et al., 2002a). This quantity is needed in order to determine the overall biomass accumulation, and resulting nutrient uptake.

$$fr_{root} = 0.40 - 0.20 \cdot fr_{PHU} \quad (73)$$

Where,  $fr_{root}$  is the fraction of the total biomass of the roots on a given day, and  $fr_{PHU}$  is the fraction of potential heat units accumulated for the plant on a given day in the growing season [dimensionless].

The above calculations assume optimal growing conditions, however, actual growth may lag behind optimal growth as a result of extremes of temperature, and insufficient water, nitrogen or phosphorus. SWAT calculates the amount of stress for each of these parameters, and sums their effects on plant growth. The discussion here will focus solely on water stress as this project is focused on the irrigation demand required to counteract the effects of water stress.

Water stress in this context can be quantified as the rate of actual evapotranspiration ( $ET_a$ ) to potential evapotranspiration ( $ET_p$ ) given identical meteorological conditions. The difference between actual and maximum evapotranspiration is a result of decreasing water availability within the root zone. In SWAT water stress is simulated by comparing water uptake or actual evapotranspiration to potential evapotranspiration as shown in equation 74 (Neitsch et al., 2002a).

$$wstrs = 1 - \frac{ET_a}{ET_p} = 1 - \frac{w_{actualup}}{ET_p} \quad (74)$$

Where,  $w_{actualup}$  is the total actual water uptake [mm H<sub>2</sub>O],  $ET_a$  is the actual evapotranspiration [mm H<sub>2</sub>O],  $ET_p$  is the potential evapotranspiration [mm H<sub>2</sub>O], and  $wstrs$  is the water stress for the given day [dimensionless].

Actual biomass production is determined by multiplying the potential biomass production by one minus the water stress factor ( $1-wstrs$ ), assuming that water stress is the predominating limiting factor. Actual leaf area index is determined by multiplying the potential leaf area index with the square root of the water stress factor (Neitsch et al., 2002a). A similar technique is used when temperature, nitrogen or phosphorus stress predominates.

Using the calculated actual biomass data, SWAT is able to determine a crop harvest value or economic yield at maturity. SWAT considers the harvest to be a fraction of the aboveground plant dry biomass (Neitsch et al., 2002a). The above biomass on the day of harvest is given by equation 75 as;

$$bio_{ag} = (1 - fr_{root}) \cdot bio \quad (75)$$

Where,  $bio_{ag}$  is the aboveground biomass on the day of harvest [kg/ha],  $bio$  is the plant biomass on the day of the harvest [kg/ha], and  $fr_{root}$  is the fraction of the total biomass in the roots [dimensionless].

Yield is related to aboveground plant biomass through the use of a potential harvest index ( $HI$ ), which varies for each crop species. Generally, the harvest index varies between 0.0 and 1.0, but may exceed 1.0 in the case where plant roots are harvested. SWAT calculates the harvest index for each day of the plant's growing season using equation 76, and uses this value in determining crop yield in equations 77a and b that follows:

$$HI = HI_{opt} \cdot \frac{100 \cdot fr_{PHU}}{(100 \cdot fr_{PHU} + \exp[11.1 - 10 \cdot fr_{PHU}])} \quad (76)$$

Where,  $HI$  is the potential harvest index for a given day [dimensionless],  $HI_{opt}$  is the potential harvest index for the plant at maturity given ideal growing seasons conditions [dimensionless], and  $fr_{PHU}$  is the fraction of potential heat units accumulated for the plant on a given day in the growing season [dimensionless].

$$yld = bio_{ag} \cdot HI \quad \text{when } HI \leq 1.00 \quad (77a)$$

$$yld = bio \cdot \left(1 - \frac{1}{(1 + HI)}\right) \quad \text{when } HI > 1.00 \quad (77b)$$

Where,  $bio_{ag}$  is the aboveground biomass on the day of harvest [kg/ha],  $bio$  is the plant biomass on the day of the harvest [kg/ha],  $yld$  is the crop yield [kg/ha], and  $HI$  is the potential harvest index for a given day [dimensionless].

The potential harvest index ( $HI$ ) is adjusted for water deficit conditions as (Neitsch et al., 2002a);

$$HI_{act} = (HI - HI_{min}) \cdot \frac{\gamma_{wu}}{\gamma_{wu} + \exp[6.13 - 0.883 \cdot \gamma_{wu}]} + HI_{min} \quad (78)$$

Where,  $HI_{act}$  is the actual harvest index [dimensionless],  $HI$  is the potential harvest index for a given day [dimensionless],  $HI_{min}$  is the harvest index for the plant and represents the minimum harvest index allowed for the plant [dimensionless],  $\gamma_{wu}$  is the water deficiency factor [dimensionless].

The water deficiency factor used in this equation is calculated using equation 79 (Neitsch et al., 2002a), which is given as the percent average of actual evapotranspiration to potential evapotranspiration for each day of the growing season until harvest.

$$\gamma_{wu} = 100 \cdot \frac{\sum_{i=1}^m E_a}{\sum_{i=1}^m E_p} \quad (79)$$

Where,  $E_a$  is the actual evapotranspiration [mm],  $E_p$  is the potential evapotranspiration [mm],  $\gamma_{wu}$  is the water deficiency factor [dimensionless],  $m$  is the day of the harvest [number], and  $i$  is the day in the plant growing season [number].

Harvest yield is then removed from the field as the final output of agricultural production. The primary objective of this study is to determine the irrigation demand required to maximize profitability primarily through increased yields. A purported benefit of maximizing output is the reduction of waste inputs, primarily nitrogen and phosphorus fertilizers that would otherwise leach into local bodies of water if not utilized, and contribute to the eventual eutrophication of the receiving bodies of water. Therefore, if the fraction of nitrogen and phosphorus contained within the crop is known, the quantity of nitrogen and phosphorus removed from the fields in the form of harvested yield under irrigated and non-irrigated conditions can be determined. This value can then be balanced against the quantity of fertilizer initially applied to the fields, in order to determine if any increase in fertilizer use efficiency exists as a result of irrigation, and a consequent reduction in nutrient wastes. The removal of nitrogen and phosphorus in the yield may be determined by equation 80a and b, respectively (Neitsch et al., 2002a):

$$yld_N = fr_{N,yld} \cdot yld \quad (80a)$$

$$yld_P = fr_{P,yld} \cdot yld \quad (80b)$$

Where,  $yld_N$  is the amount of nitrogen removed in yield [kg N/ha],  $yld_P$  is the amount of phosphorus removed in yield [kg P/ha],  $fr_{N,yld}$  is the fraction of nitrogen in yield [kg N/kg],  $fr_{P,yld}$  is the fraction of phosphorus in yield [kg P/kg], and  $yld$  is the crop yield [kg/ha].



### *Water Uptake:*

The development of plant roots has important considerations for modeling plant water uptake, which directly affects irrigation scheduling. The potential rate of water use by the plant varies with crop species, the age of the crop, and the local temperature and atmospheric conditions. Beyond the physiological aspects of the plant species and the prevailing environmental conditions, the actual rate of water uptake depends heavily on the soil-water availability within the root zone.

Both insufficient and excessive amounts of water can detract from optimal growth. Excessive flooding and filling of the soil pore spaces with water reduces aeration and inhibits proper functioning of plants by eliminating available oxygen necessary for plant metabolism, respiration and photosynthesis. Additionally, saturated conditions increase denitrification and leaching of plant nutrients (Hargreaves and Samani, 1984). On the other hand, plants must expend more energy in order to meet transpiration requirements in soils with reduced or insufficient quantities of water, resulting in lower growth rates (Isrealsen and Hansen, 1962).

As the quantity of available water is lowered, the plant is able to extract less and less water until eventually, it is unable to overcome the forces that bind the water molecules to the soil matrix. This boundary defines the lower limit of the quantity of plant available water, which is referred to as the wilting point below which permanent wilting will occur (Gardner, 1968). The permanent wilting point is defined as the soil-water content at which plants remain wilted overnight or in a humid chamber (Kramer and Boyer, 1995). The upper boundary of the soil-water is the saturation point at which all soil pores are filled with water. However, water is generally held at 'field capacity,'

due to percolation, which is achieved once saturated soils have drained under normal gravitational suction to an equilibrium soil-water conditions.

This concept of decreasing availability is more clearly understood by considering that water movement in the soil-plant-atmosphere system occurs as a result of differences in the total potential energy of the water at various points in the soil-plant system (Gardner, 1968). The water potential in the plant, and specifically within the leaves, must be lower than the water potential in the soil matrix if water is to be taken up by the plant roots and transported to the leaves. This allows for a continuous flow of water from the soil profile through the plant and into the atmosphere as a result of transpiration. This process ends once the potential difference between the soil profile water and the plant water approaches zero.

Several factors influence the potential energy associated with the water in the soil matrix. The energy level is primarily determined by attractive forces that hold the water within the soil matrix referred to as the matric potential. This matric potential is the sum of three components the adsorption, capillary and molecular attraction potential, and may be presented as (Gardner, 1968);

$$\Psi_m = \Psi_a + \Psi_c + \Psi_w \quad (81)$$

Where,  $\Psi_m$  is the matric potential [cm],  $\Psi_a$  is the adsorption potential [cm],  $\Psi_c$  is the capillary potential [cm], and  $\Psi_w$  is the molecular attraction potential [cm].

The absorption potential is the adsorption forces operating within the first few molecular layers of the particle surface. The capillary potential is the potential derived

from the curved meniscus at the air-water interface, which is a function of the surface tension ( $\sigma$ ) and the radius of curvature ( $r$ ) of the air-water interface ( $\Psi_c = -2 \sigma/r$ ). The third component of the matric potential is the result of attractive forces between the water molecules and dissolved ions in solution. The negative of the matric potential is traditionally referred to as the soil moisture tension or the soil suction expressed in centimeters of water (Gardner, 1968). The matric potential is negligible in saturated soils, but increasingly more significant in unsaturated soils.

A second component of the potential energy of the soil-water results from the external pressure ( $\Psi_p$ ), and is attributed to the weight of the water above the point of measurement as shown in equation 82. Contrary to the matric potential, the pressure potential is negligible in unsaturated soils, but is increasingly significant in saturated soils (Gardner, 1968).

$$\psi_p = v \cdot \Delta p \quad (82)$$

Where,  $\Psi_p$  is the pressure potential [cm],  $v$  is the specific volume of water [ $\text{cm}^3/\text{g}$ ],  $\Delta p$  is the hydrostatic pressure in excess of atmospheric pressure [kPa].

A third component that reduces the potential energy difference within the soil-plant system results from the earth's gravitational pull, and is shown in equation 83 (Gardner, 1968). It is the potential caused by the mass of the water being drawn downward under the force of gravity.

$$\psi_g = \rho_w g \cdot \Delta h \quad (83)$$

Where,  $\Psi_g$  is the gravitational potential [cm],  $\rho_w$  is the density of water [ $\text{kg/m}^3$ ],  $g$  is the gravitational constant [ $9.81 \text{ m/s}^2$ ], and  $\Delta h$  is the elevation above datum [m].

The sum of the three potential energy components described above per unit weight of water is referred to as the hydraulic head expressed in units of length as shown in equation 84 (Gardner, 1968);

$$H = (\psi_m + \psi_p + \psi_g) / g \quad (84)$$

Where,  $H$  is the hydraulic head [cm],  $g$  is the gravitational constant,  $\Psi_m$  is the matric potential [cm],  $\Psi_p$  is the pressure potential [cm], and  $\Psi_g$  is the gravitational potential [cm].

A fourth component of the water potential within the soil profile, which contributes to a decrease in water availability to the plants, but is not included in the determination of the hydraulic head is referred to as the osmotic potential ( $\Psi_\pi$ ), and results from the total dissolved salts in solution (Gardner, 1968). However, as the concentration of solutes in the soil profile is generally low, with the exception of saline soils, the effects of the osmotic potential can be neglected (Miyazaki, 1993).

Nevertheless, the osmotic potential becomes a critical component when considering the water potential associated with the plant system, and is essential in understanding the kinetics of water uptake and transport within plants (Miyazaki, 1993). As with the water potential associated with the soil, the water potential of the plant consists of four components: the matric potential, the osmotic potential, the pressure

potential and the gravitational potential, the sum of which must be lower than the total potential of the water associated with the soil system if water flow is to overcome impedance to movement, and flow from the soil profile into the plant system. The total water potential in the plants is shown by equation 85 (Miyazaki, 1993) as;

$$\Psi_{plant} = \Psi_m + \Psi_o + \Psi_p + \Psi_g \quad (85)$$

Where,  $\Psi_{plant}$  is the total plant water potential [cm],  $\Psi_m$  is the matric potential [cm],  $\Psi_o$  is the osmotic potential [cm],  $\Psi_p$  is the pressure potential [cm], and  $\Psi_g$  is the gravitational potential [cm].

In the case of plants, the matric potential is a result of the hydration of colloidal substances and surface tension at micro-spaces within the cell walls (Miyazaki, 1993). The osmotic pressure can be significantly different from the soil profile, and vary in strength from  $-0.5$  kJ/kg to minus several kJ/kg (Miyazaki, 1993). The pressure potential is a positive value unlike other components of the total water potential equation and acts to expand cell walls. The gravitational potential is an opposing force to water uptake by plants and results from the potential height differences that water must travel, which can be significant in the case of trees and tall plant species.

The difference between the total water potential of the plant and the total water potential within the soil profile determines the potential for water uptake by the plant, which gradually decreases over time as water becomes less available within the soil profile or when external ambient conditions do not exert significant upward suction gradient. Water absorption from the substrate to the roots occurs along gradients of

decreasing potential. This gradient is produced differently during periods of slow and rapid transpiration, resulting in two distinct absorption processes: passive absorption and active or osmotic absorption (Kramer and Boyer, 1995).

Active or osmotic absorption occurs in slowly transpiring plants, in which water is pulled into the root system as a result of dissolved mineral concentration differences within the root structure and the surrounding soil media. The increased concentration of dissolved ions within the root structure results in more water being pulled into the root system, resulting in a net positive pressure.

This positive pressure is lost once transpiration rates increase at which time passive water uptake predominates. This second mechanism predominates during periods of high transpiration peaking at midday. The force triggering this mechanism originates at the leaf surface where water is lost causing a lowering of water potential within the leaf. The drop in water potential triggers a continuous chain where water in the leaf is replaced by water pulled in from the leaf veins, which is replaced by xylem sap and so forth, until the drop in water potential is felt in the roots where water is then pulled in from the surrounding media. Under these circumstances water can be considered to be moving through the plant in a continuous column, pulled up by the matric or imbibitional forces developed at the leaf cell walls or the evaporating surface (Kramer and Boyer, 1995).

In such a system the driving radiant energy, which controls transpiration, fluctuates within a 24-hour period. As a result leaf water potential mirror a diurnal oscillation generally reaching its maximum value at sunrise, and its lowest point between midday and mid-afternoon (Stegman, 1983). Therefore, peak water demand generally

occurs at midday, corresponding to the lowest point of the water potential within the plant.

The relative degree of the leaf's water potential drop is dependent on the evaporation demand. The energy received produces this evaporation demand, however the rate at which water can be supplied for transpiration is regulated by the water potential difference between the soil and plant. The potential difference between the leaf water and soil-water potential is generally greatest when the leaf water potential is lowest. At this time water uptake and transpiration is highest as indicated by equation 61 (Childs et al., 1977). However, as the water potential associated with the soil-water drops with decreasing availability, the potential for transpiration decreases.

$$T = \frac{\Psi_{plant} - \Psi_{soil}}{r_{sr} + r_p} \quad (86)$$

Where,  $T$  is the transpiration [cm],  $\Psi_{plant}$  is the total plant water potential [cm],  $\Psi_{soil}$  is the total soil-water potential [cm],  $r_{sr}$  is the flow resistance in soil pathway [dimensionless], and  $r_p$  is the flow resistance in plant pathway [dimensionless].

As available water is depleted in the soil profile, the maximum potential difference between the leaf water potential and the soil-water potential is decreased, thereby reducing the uptake potential of the plant, which negatively affects plant evapotranspiration rates. Given this relationship it is possible, through empirical methods and local calibration, to obtain estimates of actual evapotranspiration based on available water remaining in the root zone (Stegman, 1983). The plant will continue to uptake water and transpire at a reduced level until the leaf and soil-water potential difference

approaches zero, at which time residual water remaining in the soil profile will be unavailable to the crop and permanent wilting will ensue.

The hydraulic head value at which the water becomes unavailable to plants depends heavily on the rooting depth. Intuitively, shallow rooted crops require more frequent irrigation, while more deeply rooted plants are able to access water contained within deeper soil levels and therefore require less frequent irrigation (Israel and Hansen, 1962).

Nevertheless, while the depth to which plant roots might extend varies with the crop species, the density of the roots is greatest in the upper portion of the root zone near the soil surface (Miyazaki, 1993). As a result of this root density pattern, plants extract water preferentially from the shallow layers, when the soil profile is wet. Plants begin to extract greater amounts of water from lower zones, within the root profile, as the upper layers begin to dry. Nevertheless, the younger roots associated with the deeper levels extract proportionally more water per unit length, than do the older roots associated with the upper layers given the same root density (Miyazaki, 1993).

As a result of the complexity of water uptake, SWAT models plant uptake in three phases. When soil-water content levels are high and water is readily available to the plant, SWAT models water uptake such that water is removed preferentially from the upper layers of the soil until the available water is insufficient to meet the plant needs, at which time the equation variables are revised such that an increasing amount of water is removed from the lower layers depending on the water demand. As the water content in the soil continues to decrease (below 25% of available water), and the plants exert more



energy to uptake the remaining amount of water, a revised exponential equation is used, which is a function of the soil-water content (Neitsch et al., 2002a).

When water is plentiful, the potential water uptake is given by equation 87, with the relative proportion of water uptake from upper and lower soil layers being determined by equations 88 and 89 that follow (Neitsch et al., 2002a):

$$w_{up,z} = \frac{ET_p}{1 - \exp(-\beta_w)} \cdot \left[ 1 - \exp\left(-\beta_w \cdot \frac{z}{z_{root}}\right) \right] \quad (87)$$

Where,  $w_{up,z}$  is the potential water uptake from the soil profile at a specified depth  $z$  [mm of H<sub>2</sub>O],  $ET_p$  is the potential evapotranspiration [mm],  $\beta_w$  is the water use distribution parameter [dimensionless],<sup>35</sup>  $z$  is the depth from the soil surface [mm],  $z_{root}$  is the depth of root development in the soil [mm], and  $r_p$  is the flow resistance in plant pathway [dimensionless].

The water-use distribution parameter ( $\beta_w$ ) is set to 10 in SWAT, which dictates that 50% of the water is removed from the upper 6% of the root zone, while the remaining 50% of the water is removed from the lower 94%. Since SWAT models water movement in layers of soil, the potential water uptake in any given layer is determined by solving for the water uptake potential at the top and bottom depth and taking the difference as shown in equation 88 (Neitsch et al., 2002a).

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<sup>35</sup> Water-use distribution parameter ( $\beta_w$ ) is set to 10 in SWAT (Neitsch et al., 2002a).

$$w_{up,ly} = w_{up,lu} - w_{up,zu} \quad (88)$$

Where,  $w_{up,ly}$  is the potential water uptake for layer  $ly$  [mm of H<sub>2</sub>O],  $w_{up,zl}$  is the potential water uptake for lower boundary [mm of H<sub>2</sub>O], and  $w_{up,zu}$  is the potential water uptake for upper boundary [mm of H<sub>2</sub>O].

This potential water uptake equation is modified when water is insufficient in the upper soil layers to meet demand. The adjusted potential water uptake for a given layer is given by the equation below (Neitsch et al., 2002a). The plant uptake compensation factor ( $epco$ ) varies between 0 and 1.0, and determines the degree to which lower layers can compensate for insufficient water in the upper layers. This value varies with plant species.

$$w'_{up,ly} = w_{up,ly} - w_{demand} \cdot epco \quad (89)$$

Where,  $w'_{up,ly}$  is the adjusted potential water uptake for layer  $ly$  [mm of H<sub>2</sub>O],  $w_{up,ly}$  is the potential water uptake for layer  $ly$  [mm of H<sub>2</sub>O],  $w_{demand}$  is the water uptake demand not meet by overlaying layer [mm of H<sub>2</sub>O], and  $epco$  is the plant uptake compensation factor [dimensionless].

The adjusted potential water uptake value is used when the soil-water content is greater than or equal to 25% of the total available water capacity for the layer under review. Once the soil-water content drops below 25 percent of the available water capacity, the potential water uptake is adjusted using equation 90 (Neitsch et al., 2002a) as;

$$w''_{up,ly} = w'_{up,ly} \cdot \exp \left[ 5 \cdot \left( \frac{\theta_{ly}}{(0.25 \cdot AWC_{ly})} - 1 \right) \right] \quad (90)$$

Where,  $w''_{up,ly}$  is the potential water uptake adjusted for initial soil-water content [mm of H<sub>2</sub>O],  $w'_{up,ly}$  is the adjusted potential water uptake for layer  $ly$  [mm of H<sub>2</sub>O],  $\theta_{ly}$  is the soil-water content of layer  $ly$  [mm of H<sub>2</sub>O], and  $AWC_{ly}$  is the available water capacity for layer  $ly$  [mm of H<sub>2</sub>O].

The actual water uptake is the sum of the water uptake for each layer, which is also equivalent to the actual evapotranspiration for that day as given by equation 91.

$$w_{actualup} = \sum_{ly=1}^n w_{actual,ly} = ET_a \quad (91)$$

Where,  $w_{actualup}$  is the total actual water uptake [mm of H<sub>2</sub>O],  $w_{actual,ly}$  is the actual water uptake for layer  $ly$  [mm of H<sub>2</sub>O], and  $ET_a$  is the actual evapotranspiration [mm of H<sub>2</sub>O].

Other factors modeled in the SWAT model, with less importance to irrigation application, are briefly outlined in the pages that follow, and are included in order to give a brief overview of the potential capabilities and operation of the SWAT model.

Furthermore, changing hydrologic patterns in a given area, by implementing a given irrigation schedule, will induce different biochemical processes in the soil and will have environmental consequences.

### *Agricultural Management:*

SWAT allows the user to define management practices by specifying the beginning and ending of the growing season, the timing and amounts of fertilizer, and pesticide application, the harvest operation, field tillage and grazing effects, the use of filter strips and water management practices (Neitsch et al., 2002a). Water management practices include periodic or auto-application irrigation, tile drainage, water consumptive use, and water transfers.

Water applications can be applied from any source within or outside of the watershed including reservoirs, reaches and subbasins, and can be exported to outside of the watershed. Water removed or applied is then reflected in the overall hydrology model. In modeling irrigation application the user must specify the quantity to be applied the irrigation timing and the source of the water. Accurately modeling these water management practices can be the most complicated portions of the data input (Neitsch et al., 2002a).

### *Erosion and Sedimentation:*

Erosion and sedimentation yield is calculated for each HRU defined within the SWAT model using equation 92 known as the Modified Universal Soil Loss Equation (MUSLE). Equation 92 incorporates surface runoff and peak runoff values calculated in the hydrological component of the model, as well as factors included for land cover and erodibility, based on agricultural practices. The modified soil loss equation, and the corresponding equation factors and components, are taken from Wischmeier and Smith (1978). The specific values for individual plant species agricultural practices, soil

conditions are contained within a standard database files included with the SWAT software, and can be obtained from the official SWAT website.<sup>36</sup>

$$Y_{ield} = 11.8(V \cdot Q_p \cdot A_{hru})^{0.56}(K)(C)(P)(LS) \quad (92)$$

Where,  $Y_{ield}$  is the sediment yield from subwatershed [metric tons],  $V$  is the surface runoff volume [ $m^3$ ],  $Q_p$  is the peak runoff rate [ $m^3/s$ ],  $A_{hru}$  is the area of the hydrologic response unit [ha],  $K$  is the soil erodibility factor [dimensionless],  $C$  is the crop management factor [dimensionless],  $P$  is the erosion control practice factor [dimensionless], and  $LS$  is the slope length and steepness factor [dimensionless].

#### *Nutrients:*

SWAT models both nitrogen and phosphorus concentrations entering and exiting the soil profile. The amount of nitrogen ( $NO_3-N$ ) in the runoff is estimated as the product of the volume of runoff and the concentration within the first layer of the top soil (a 10 mm thickness); while the amount of nitrogen in the lateral subsurface flow is calculated as the product of the water volume and the nitrogen concentration within each individual layer. Nitrogen and phosphorus concentrations will be compared with and without irrigation in order to determine the environmental impact that irrigation may have on the transport and loading of nutrients into local rivers and streams.

The total amount of organic nitrogen transported with the sediment is calculated based on a loading function, which is determined by the concentration of organic nitrogen in the topsoil layer, the sediment yield and the enrichment ratio (mass of organic

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<sup>36</sup> Available on the world wide web: (<http://www.brc.tamus.edu/swat>).

nitrogen in the sediment per unit mass of soil). The amount of nitrogen taken up by the plants is estimated using a supply and demand approach. The following is used to determine the concentration of nitrate in the soil-water at each soil layer (Neitsch et al., 2002a):

$$C_{NO_3,m} = \frac{NO_3_{ly} \exp\left[\frac{-w_{mobile}}{(1-\theta_e) \cdot \theta_{e,ly}}\right]}{w_{mobile}} \quad (93)$$

Where,  $C_{NO_3,m}$  is the concentration of nitrate in the mobile water for a given layer [kg N/mm of water],  $NO_3_{ly}$  is the amount of nitrate in the layer [kg N/ha],  $w_{mobile}$  is the amount of mobile water in layer [mm],  $\theta_e$  is the fraction of porosity from which anions are excluded, and  $\theta_{s,ly}$  is the saturated water content of the soil layer [mm].

The amount of phosphorus loss is calculated using a similar approach with the exception that the amount of phosphorus removed in the runoff is estimated as the product of the concentration of labile P in the top 10 mm of the soil, the volume of the runoff, and a partitioning factor. This is due to the fact that phosphorus is far less soluble and therefore much of it remains bond to the soil particles. Concentration of soluble phosphorus taken up by the surface runoff is defined as (Neitsch et al., 2002a);

$$P_{surf} = \frac{P_{solution,surf} \cdot Q_{surf}}{\rho_b \cdot d_{surf} \cdot k_{d,surf}} \quad (94)$$

Where,  $P_{surf}$  is the soluble phosphorus lost in surface runoff [kg P/ha],  $P_{sol,surf}$  is the phosphorus in solution in the top 10 mm [kg P/ha],  $Q_{surf}$  is the amount of surface runoff on a given day [mm],  $\rho_b$  is the bulk density of the top 10 mm [Mg/m<sup>3</sup>],  $d_{surf}$  is the depth of the surface layer [10 mm], and  $k_{d,surf}$  is the phosphorus soil partitioning coefficient [m<sup>3</sup>/Mg].

*Pesticides:*

Equations used to model the movement of pesticides in the land phase of hydrologic cycle are adapted from the GLEAMS model. These equations use the solubility and the chemical half-life of the pesticide, and the organic carbon adsorption coefficient of the soil to determine pesticide concentrations. Pesticide transport by water and sediment is calculated for each runoff event, while pesticide leaching is estimated for each soil layer in which percolation occurs (Neitsch et al., 2002a).

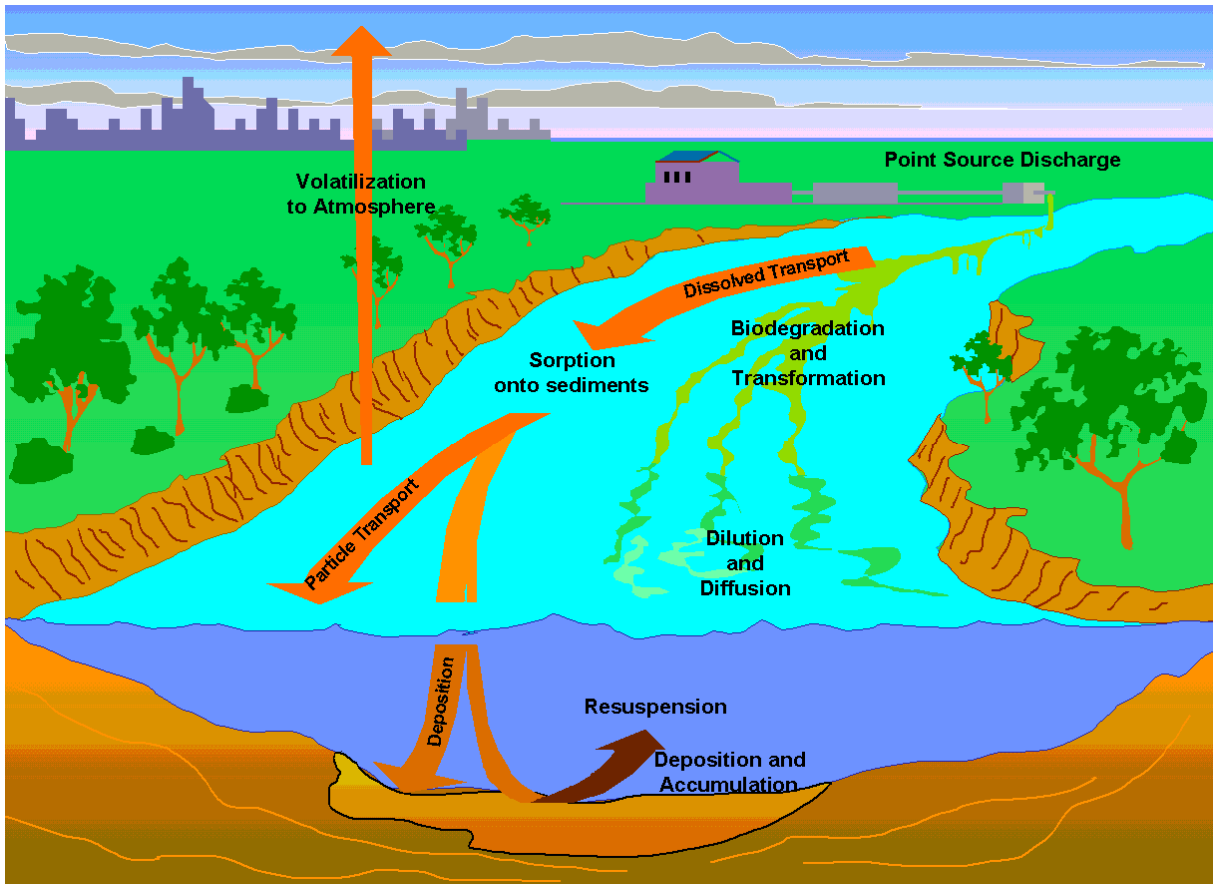
*Soil Temperature:*

Soil temperature affects the movement of water and the decomposition of organic matter in the soil. Surface soil temperature is calculated as a function of snow cover, plant and residual cover, the bare soil surface temperature and the previous day's soil surface temperature. For each subsequent layer the soil temperature is calculated as a function of surface temperature, the mean annual temperature and the depth of the soil at which soil temperature fluxuations, due to surface temperature changes, no longer occur. Calculated soil temperatures are then used to determine decomposition rates and water flow through the soil profile (Neitsch et al., 2002a).

*Routing:*

Once water, sediment, nutrient and pesticide loadings to the main channel are determined for each individual HRU, the loadings are routed through the stream network of the overall watershed. In addition to mass flow, SWAT keeps track of chemical transformations within the stream and streambed. Routing in the main channel is divided into four components: water, sediment, nutrients, and organic chemicals. The routing of each of these components is modeled individually for both stream and reservoirs. These in-stream processes include chemical transformation, degradation, volatilization, sorption, sediment deposition or resuspension, and bioaccumulation. All of these processes may occur as the nutrients, agricultural chemicals, and sediments are transported along the stream based upon the modeled hydrologic conditions and specified parameters. An illustration of these processes is shown in Figure 45 (Neitsch et al., 2002a).





**Figure 45.** In-stream processes modeled by SWAT.<sup>37</sup>

<sup>37</sup> Figure obtained from Blackland Research and Extension Center. Available WWW: [http://www.brc.tamus.edu/swat/newmanual/intro/overview\\_route.html](http://www.brc.tamus.edu/swat/newmanual/intro/overview_route.html)

## Appendix B: SCS Curve Numbers for Runoff Calculations

The following is a list of SCS curve numbers obtained from the SWAT User's Manual, used in the determination of runoff values (Neitsch et al., 2002a).

**Table 31.** Runoff curve numbers for cultivated agricultural lands (SCS Engineering Division, 1986)

Land Use:	Treatment or Practice:	Hydrologic Condition:	Hydrologic Soil Group			
			A	B	C	D
Fallow	Bare soil	----	77	86	91	94
	Crop residue cover	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row with residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured with residue	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured and terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured and terraced with residue	Poor	65	73	79	81
		Good	61	70	77	80
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row with residue	Poor	64	75	83	86
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured with residue	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured and terraced with residue	Poor	60	71	78	81
		Good	58	69	77	80
Close seeded or broadcast legumes or rotations	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured with terraced	Poor	63	73	80	83
		Good	51	67	76	80

**Table 32.** Runoff curve numbers for other agricultural lands (SCS Engineering Division, 1986)

Crop Type:	Hydrologic Condition:	Hydrologic Soil Group			
		A	B	C	D
Pasture, grassland, or range –continuous forage for grazing	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow –continuous grass, protected from grazing and generally mowed for hay	- - - -	30	58	71	78
Brush –brush-weed-grass mixture with brush the major element	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30	48	65	73
Woods –grass combination (orchard or tree farm)	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77
Farmsteads –buildings, lanes, driveways, and surroundings lots.	Poor	59	74	82	86

**Table 33.** Runoff curve numbers for urban areas (SCS Engineering Division, 1986)

Crop Type:	Hydrologic Condition:	Average % Impervious Area	Hydrologic Soil Group			
			A	B	C	D
<i>Developed Urban Area:</i>						
Open spaces (lawns, parks, golf courses, cemeteries, etc.)	Poor		68	79	86	89
	Fair		49	69	79	84
	Good		39	61	74	80
<i>Impervious Areas:</i>						
Paved parking lots, roofs, driveways etc.	----		98	98	98	98
Paved streets and roads; open ditches	----		83	89	82	93
Gravel streets and roads	----		76	85	89	91
Dirt streets and roads	----		72	82	87	89
<i>Urban Districts:</i>						
Commercial and business		85%	89	92	94	95
Industrial		72%	81	88	91	93
Residential districts by average lot size						
1/8 acre (0.05 ha) or less		65%	77	85	90	92
1/4 acre (0.10 ha)		38%	61	75	83	87
1/3 acre (0.13 ha)		30%	57	72	81	86
1/2 acre (0.20 ha)		25%	54	70	80	85
1 acre (0.40 ha)		20%	51	68	79	84
2 acre (0.81 ha)		12%	46	65	77	82
<i>Developing Urban Areas:</i>						
Newly graded areas (previous areas only)			77	86	91	94

## Appendix C: SWAT Land Cover Input Variables

The table below lists all plant species for which the physical variable values are already included in the SWAT's internal crop/land cover database. The list includes the majority of the economically valuable crop species as well as some generic land cover species.

**Table 34.** Plant species included in the SWAT plant growth database

Common Name:	Plant Code:	Taxonomic Name:	Plant Type:
Corn	CORN	<i>Zea mays</i> L.	warm season annual
Corn silage	CSIL	<i>Zea mays</i> L.	warm season annual
Sweet corn	SCRN	<i>Zea mays</i> L.saccharata	warm season annual
Eastern gamagrass	EGAM	<i>Tripsacum dactyloides</i> (L.) L.	perennial
Grain sorghum	GRSG	<i>Sorghum bicolor</i> L. (Moench)	warm season annual
Sorghum hay	SGHY	<i>Sorghumbicolor</i> L. (Moench)	warm season annual
Johnsongrass	JHGR	<i>Sorghum halepense</i> (L.)Pers.	perennial
Sugarcane	SUGC	<i>Saccharum officinarum</i> L.	perennial
Spring wheat	SWHT	<i>Triticum aestivum</i> L.	cool season annual
Winter wheat	WWHT	<i>Triticum aestivum</i> L.	cool season annual
Durum wheat	DWHT	<i>Triticum durum</i> Desf.	cool season annual
Rye	RYE	<i>Secale cereale</i> L.	cool season annual
Spring barley	BARL	<i>Hordeum vulgare</i> L.	cool season annual
Oats	OATS	<i>Avena sativa</i> L.	cool season annual
Rice	RICE	<i>Oryza sativa</i> L.	warm season annual
Pearl millet	PMIL	<i>Pennisetum glaucum</i> L.	warm season annual
Timothy	TIMO	<i>Phleum pratense</i> L.	perennial
Smooth brome grass	BROS	<i>Bromus inermis</i> Leysser	perennial
Meadow brome grass	BROM	<i>Bromus biebersteinii</i> Roemer & Schultes	perennial
Tall fescue	FESC	<i>Festuca arundinacea</i>	perennial
Kentucky bluegrass	BLUG	<i>Poa pratensis</i>	perennial
Bermudagrass	BERM	<i>Cynodon dactylon</i>	perennial
Crested wheatgrass	CWGR	<i>Agropyron cristatum</i> (L.) Gaertner	perennial
Western wheatgrass	WWGR	<i>Agropyron smithii</i> (Rydb.) Gould	perennial
Slender wheatgrass	SWGR	<i>Agropyron trachycaulum</i> Malte	perennial
Italian (annual) ryegrass	RYEG	<i>Lolium multiflorum</i> Lam.	cool season annual
Russian wildrye	RYER	<i>Psathyrostachys juncea</i> (Fisch.) Nevski	perennial

<b>Common Name:</b>	<b>Plant Code:</b>	<b>Taxonomic Name:</b>	<b>Plant Type:</b>
Altai wildrye	RYEA	<i>Leymus angustus</i> (Trin.) Pilger	perennial
Sideoats grama	SIDE	<i>Bouteloua curtipendula</i> (Michaux) Torrey	perennial
Big bluestem	BBLS	<i>Andropogon gerardii</i> Vitman	perennial
Little bluestem	LBSL	<i>Schizachyrium scoparium</i> (Michaux) Nash	perennial
Alamo switchgrass	SWCH	<i>Panicum virgatum</i> L.	perennial
Indiangrass	INDN	<i>Sorghastrum nutans</i> (L.) Nash	perennial
Alfalfa	ALFA	<i>Medicago sativa</i> L.	perennial legume
Sweetclover	CLVS	<i>Melilotus alba</i> Med.	perennial legume
Red clover	CLVR	<i>Trifolium pratense</i> L.	cool season annual legume
Alsike clover	CLVA	<i>Trifolium hybridum</i> L.	perennial legume
Soybean	SOYB	<i>Glycine max</i> L., Merr.	warm season annual legume
Cowpeas	CWPS	<i>Vigna sinensis</i>	warm season annual legume
Mung bean	MUNG	<i>Phaseolus aureus</i> Roxb.	warm season annual legume
Lima beans	LIMA	<i>Phaseolus lunatus</i> L.	warm season annual legume
Lentils	LENT	<i>Lens esculenta</i> Moench J.	warm season annual legume
Peanut	PNUT	<i>Arachis hypogaea</i> L.	warm season annual legume
Field peas	FPEA	<i>Pisum arvense</i> L.	cool season annual legume
Garden or canning peas	PEAS	<i>Pisum sativum</i> L. ssp. sativum	cool season annual legume
Sesbania	SESB	<i>Sesbania macrocarpa</i> Muhl	warm season annual legume
Flax	FLAX	<i>Linum usitatissimum</i> L.	cool season annual
Upland cotton (harvested with stripper)	COTS	<i>Gossypium hirsutum</i> L.	warm season annual
Upland cotton (harvested with picker)	COTP	<i>Gossypium hirsutum</i> L.	warm season annual
Tobacco	TOBC	<i>Nicotiana tabacum</i> L.	warm season annual
Sugar beet	SGBT	<i>Beta vulgaris</i> (saccharifera) L.	warm season annual
Potato	POTA	<i>Solanum tuberosum</i> L.	cool season annual
Sweet potato	SPOT	<i>Ipomoea batatas</i> Lam.	warm season annual
Carrot	CRRT	<i>Daucus carota</i> L. subsp. sativus (Hoffm.) Arcang.	cool season annual
Onion	ONIO	<i>Allium cepa</i> L. var cepa	cool season annual
Sunflower	SUNF	<i>Helianthus annuus</i> L.	warm season annual
Spring canola-Polish	CANP	<i>Brassica campestris</i>	cool season annual

<b>Common Name:</b>	<b>Plant Code:</b>	<b>Taxonomic Name:</b>	<b>Plant Type:</b>
Spring canola-Argentine	CANA	Brassica napus	cool season annual
Asparagus	ASPR	Asparagus officinalis L.	perennial
Broccoli	BROC	Brassica oleracea L. var italica Plenck.	cool season annual
Cabbage	CABG	Brassica oleracea L. var capitata L.	perennial
Cauliflower	CAUF	Brassica oleracea L. var botrytis L.	cool season annual
Celery	CELR	Apium graveolens L. var dulce (Mill.) Pers.	perennial
Head lettuce	LETT	Lactuca sativa L. var capitata L.	cool season annual
Spinach	SPIN	Spinacia oleracea L.	cool season annual
Green beans	GRBN	Phaseolus vulgaris	warm season annual legume
Cucumber	CUCM	Cucumis sativus L.	warm season annual
Eggplant	EGGP	Solanum melongena L.	warm season annual
Cantaloupe	CANT	Cucumis melo L. Cantaloupensis group	warm season annual
Honeydew melon	HMEL	Cucumis melo L. Inodorus group	warm season annual
Watermelon	WMEL	Citrullus lanatus (Thunb.) Matsum and Nakai	warm season annual
Bell pepper	PEPR	Capsicum annuum L. Grossum group	warm season annual
Strawberry	STRW	Fragaria X Ananassa Duchesne.	perennial
Tomato	TOMA	Lycopersicon esculentum Mill.	warm season annual
Apple	APPL	Malus domestica Borkh.	trees
Pine	PINE	Pinus	trees
Oak	OAK	Quercus	trees
Poplar	POPL	Populus	trees
Honey mesquite	MESQ	Prosopis glandulosa Torr. var. glandulosa	trees

SWAT does include a series of additional generic land cover codes used when a more general land cover category is needed. However, the parameter values used for these generic land covers are the same as a representative crop of the category described. Table 35 lists the generic land cover codes as well as the specific crop from which the parameter values used are taken from.

**Table 35.** Generic land covers included in the SWAT plant growth database

<b>Common Name/ Description:</b>	<b>Plant Code:</b>	<b>Parameter Values Referenced:</b>	<b>Plant Type:</b>
Agricultural Land- Generic	AGRL	Values same as Grain Sorghum	warm season annual
Agricultural Land- Row Crops	AGRR	Values same as Corn	warm season annual
Agricultural Land- Close-grown	AGRC	Values same as Winter Wheat	cool season annual
Orchard	ORCD	Values same as Apples	trees
Hay	HAY	Values same as Bermudagrass	perennial
Forest-mixed	FRST	Values same as Oak	trees
Forest-deciduous	FRSD	Values same as Oak	trees
Forest-evergreen	FRSE	Values same as Pine	trees
Wetlands	WETL	Values same as Alamo Switchgrass	perennial
Wetlands-forested	WETF	Values same as Oak	trees
Wetlands- nonforested	WETN	Values same as Alamo Switchgrass	perennial
Pasture	PAST	Values same as Bermudagrass	perennial
Summer pasture	SPAS	Values same as Bermudagrass	perennial
Winter pasture	WPAS	Values same as Fescue	perennial
Range-grasses	RNGE	Values same as Little Bluestem (LAI <sub>max</sub> =2.5)	perennial
Range-brush	RRGB	Values same as Little Bluestem (LAI <sub>max</sub> =2.0)	perennial
Range- southwestern US	SWRN	Values same as Little Bluestem (LAI <sub>max</sub> =1.5)	perennial
Water	WATR	not applicable	not applicable

Each land use classification and the corresponding coverage area, as well as the relative percentage of the watershed are presented in Table 36. This table lists the equivalent or nearest equivalent SWAT classification defined in the incorporated look-up table as opposed to the categories designated by the USGS in the NLCD grid itself, as discussed in the *Methods and Procedures* section of this study.



**Table 36.** Land use classifications and relative coverage area for the Pocomoke watershed.

Land Use:	SWAT Code:	Area [ha]:	Area [acres]:	Percentage of Watershed [%]:
Agricultural Land-Row Crops	AGRR	32579.5	80505.6	27.88
Forest-Evergreen	FRSE	27093.4	66949.2	23.19
Wetlands-Forested	WETF	19833.6	49009.9	16.97
Forest-Deciduous	FRSD	12071.1	29828.4	10.33
Forest-Mixed	FRST	10540.8	26046.9	9.02
Pasture	PAST	9557.1	23616.1	8.18
Southwestern US (Arid) Range	SWRN	2866.9	7084.2	2.45
Wetlands-Non-Forested	WETN	1048.1	2589.8	0.90
Residential-Low Density	URLD	647.0	1598.8	0.55
Commercial	UCOM	362.6	895.9	0.31
Water	WATR	231.5	572.1	0.20
Residential-High Density	URHD	14.2	35.1	0.01
Totals:		116845.9	288732.1	100.00

The table above describes the watershed as a whole, however the subset of land use classifications included in each subbasin and their relative proportion of land areas varies for each of the 79 subbasins. The relative size of each of these subbasins and the quantity of agricultural cropland they contain is included in Table 37. This table presents only the area of cropland for each subbasin, as this is most relevant to the current study.

**Table 37.** Percentage of agricultural cropland included in each subbasin and the relative size of each subbasin of the modeled watershed.

Subbasin #:	Area [ha]:	Subbasin % of Watershed:	Crop Land [ha]:	Agricultural Land % of Subbasin:
1	1260.6	1.08	593.7	47.1
2	1534.0	1.31	678.2	44.21
3	3.0	0	0.5	18.18
4	2642.1	2.26	965.7	36.55
5	1297.8	1.11	610.3	47.02
6	1693.4	1.45	1014.2	59.89
7	943.7	0.81	397.8	42.15
8	1722.4	1.47	442.5	25.69
9	1198.8	1.03	712.0	59.39

Subbasin #:	Area [ha]:	Subbasin % of Watershed:	Crop Land [ha]:	Agricultural Land % of Subbasin:
10	194.6	0.17	47.3	24.29
11	1470.2	1.26	591.7	40.25
12	1511.5	1.29	612.4	40.52
13	2461.6	2.11	1307.8	53.13
14	1620.6	1.39	560.8	34.6
15	854.2	0.73	247.8	29.01
16	1809.0	1.55	554.1	30.63
17	1896.5	1.62	489.6	25.81
18	1533.7	1.31	686.2	44.74
19	2061.4	1.76	612.2	0.52
20	1103.1	0.94	335.6	30.42
21	1069.2	0.92	332.1	31.06
22	2185.2	1.87	654.8	29.97
23	1916.1	1.64	830.8	43.36
24	1573.5	1.35	469.9	29.87
25	305.6	0.26	95.6	31.28
26	2213.9	1.89	627.4	28.34
27	1484.9	1.27	174.0	11.72
28	1284.8	1.1	358.4	27.89
29	1467.4	1.26	518.5	35.33
30	1898.0	1.62	203.8	10.74
31	233.5	0.2	2.2	0.93
32	1185.7	1.01	3.9	0.33
33	287.9	0.25	96.2	33.43
34	1683.2	1.44	607.5	36.09
35	1530.8	1.31	284.9	18.61
36	635.7	0.54	30.4	4.79
37	1133.1	0.97	95.7	8.44
38	478.6	0.41	24.8	5.17
39	778.3	0.67	148.1	19.03
40	1664.0	1.42	46.4	2.79
41	1376.6	1.18	585.5	42.53
42	1642.1	1.41	626.0	38.12
43	1032.4	0.88	408.0	39.52
44	889.4	0.76	300.5	33.79
45	340.6	0.29	191.5	56.22
46	4041.7	3.46	783.4	19.38
47	2629.5	2.25	828.7	31.52
48	1130.9	0.97	273.9	24.22
49	1941.4	1.66	493.5	25.42
50	1544.0	1.32	385.3	24.96
51	3348.0	2.87	373.5	11.16
52	985.2	0.84	49.6	5.04
53	5052.5	4.32	818.2	16.19

Subbasin #:	Area [ha]:	Subbasin % of Watershed:	Crop Land [ha]:	Agricultural Land % of Subbasin:
54	73.7	0.06	4.2	5.67
55	1659.3	1.42	421.5	25.4
56	2808.7	2.4	465.2	16.56
57	1955.4	1.67	229.0	11.71
58	959.5	0.82	39.7	4.14
59	1377.5	1.18	390.5	28.35
60	1152.7	0.99	290.4	25.19
61	1821.1	1.56	439.7	24.14
62	358.7	0.31	6.9	1.92
63	2259.7	1.93	740.1	32.75
64	1519.7	1.3	96.4	6.34
65	517.1	0.44	51.6	9.97
66	1677.0	1.44	513.7	30.63
67	1033.1	0.88	270.3	26.16
68	1241.4	1.06	278.9	22.46
69	1711.4	1.46	625.8	36.57
70	1806.3	1.55	695.4	38.5
71	577.5	0.49	123.2	21.33
72	968.9	0.83	271.7	28.04
73	1576.9	1.35	340.2	21.57
74	1511.6	1.29	359.7	23.8
75	1417.7	1.21	411.3	29.01
76	2051.6	1.76	580.8	28.31
77	1296.3	1.11	452.6	34.92
78	3025.9	2.59	1098.8	36.31
79	711.7	0.61	198.8	27.93

A list of the physical variables included in the land cover database is outlined in Table 38. The table includes the variable code used by the SWAT model and a brief description of each variable. The SWAT land cover database includes a value for each of the variables listed below for each crop species and land cover category included in the database.

**Table 38.** List of variables contained within the standard land cover database provided by SWAT (crop.dat)

Variable Name:	Variable Code:	Variable Definition:
<i>Temperature Response Variables:</i>		
$T_{base}$	T_BASE	Minimum or base temperature
$T_{opt}$	T_OPT	Optimal temperature
<i>Leaf Area Development Variables:</i>		
$LAI_{max}$	BLAI	Maximum leaf area index
$fr_{PHU,1}$	FRGRW1	Fraction of potential heat units at which $fr_{LAI,1}$ is measured
$fr_{LAI,1}$	LAIMX1	Fraction of leaf area index at $fr_{phu,1}$
$fr_{PHU,2}$	FRGRW1	Fraction of potential heat units at which $fr_{LAI,2}$ is measured
$fr_{LAI,2}$	LAIMX2	Fraction of leaf area index at $fr_{phu,2}$
$fr_{PHU,sen}$	DLAI	
<i>Energy and Biomass Conversion Variables:</i>		
$RUE$	BIO_E	Radiation use efficiency under ideal growing conditions
$\Delta r_{ue,dcl}$	WAVP	Impact of reduce vapor pressure
$RUE_{hi}$	BIOEHI	Impact of elevated CO <sub>2</sub> concentration on the RUE
$CO_{2hi}$	CO2HI	Elevated CO <sub>2</sub> concentration
<i>Stomatal Conductance Variables:</i>		
$g_{l,mx}$	GSI	Maximum stomatal conductance
$fr_{rmax}$	FRGMAX	Fraction of the maximum stomatal conductance
$vfr_{rmax}$	VPDFR	Vapor pressure deficit corresponding to $fr_{rmax}$
<i>Canopy Height and Root Development Variables:</i>		
$h_{c,mx}$	CHTMX	Maximum canopy height
$z_{root,mx}$	RDMX	Maximum root depth
$C_{USLE,mn}$		Minimum USLE C factor for land cover
<i>Plant Nutrient Content Variables:</i>		
$fr_{N,1}$	BN(1)	Nitrogen content shortly after emergence
$fr_{N,2}$	BN(2)	Nitrogen content near middle of season
$fr_{N,3}$	BN(3)	Nitrogen content at maturity
$fr_{P,1}$	BP(1)	Phosphorus content shortly after emergence
$fr_{P,2}$	BP(2)	Phosphorus content near middle of season
$fr_{P,3}$	BP(3)	Phosphorus content at maturity
<i>Harvest Variables:</i>		
$HI_{opt}$	HVSTI	Potential harvest index for optimal growth
$HI_{min}$	WSYF	Harvest index for stressed growing conditions
$fr_{N,yld}$	CNYLD	Fraction of nitrogen in harvested biomass
$fr_{P,yld}$	CPYLD	Fraction of phosphorus in harvested biomass

Temperature response variables include the minimum or base temperature ( $T_{base}$ ), and the optimal temperature ( $T_{opt}$ ). The base temperature varies with the growth stage of the plant, however, this minor variation is ignored in SWAT and a constant value is used

throughout the growth cycle. Base temperature is used to calculate the number of heat units accumulated each day, while the optimal temperature is used to determine the temperature range over which growth occurs normally, and the temperature at which heat stress occurs.

Variables used to determine leaf area development include the fraction of the total leaf area index at two stages in development ( $fr_{LAI,1}$  and  $fr_{LAI,2}$ ), associated with two potential heat unit stages ( $fr_{PHU,1}$  and  $fr_{PHU,2}$ ), as well as the maximum leaf area index ( $LAI_{max}$ ). These variables determine the leaf area index at specific stages in the growth cycle of the plant, and are important variables in determining the potential evapotranspiration rate at each stage.

Variables associated with energy and biomass conversion include the radiation use efficiency ( $RUE$ ), which quantifies the efficiency of the plant in converting light energy into biomass. The database also includes a measure of the impact of reduced vapor pressure ( $\Delta r_{ue_{dcl}}$ ), and the impact of elevated CO<sub>2</sub> concentrations on radiation use efficiency ( $RUE_{hi}$ ) for a given CO<sub>2</sub> concentration increase ( $CO_{2hi}$ ) due to greenhouse effects.

Variables related to stomatal conductance include the maximum stomatal conductance ( $GSI$ ), and two factors related to the impact of vapor pressure deficit on stomatal conductance: the fraction of maximum stomatal conductance ( $FRGMAX$ ) set to 0.75, and the vapor pressure deficit corresponding to the fraction ( $VPDFR$ ). These variables are needed in the case where the Penman-Monteith equation is used to calculate evapotranspiration rates, as is the case in this study.

Also included in the database are maximum height of the canopy ( $h_{c, mx}$ ) and the maximum rooting depth ( $z_{root, mx}$ ). Rooting depth is a particularly important factor in determining available water within the root zone and is, therefore, used in the irrigation component of the model. The land cover database also includes information on nitrogen and phosphorus content for each of the plant species at three different stages in plant development: shortly after emergence, middle of the growing season and at maturity. These values are used to determine the amount of nutrients removed from the soil profile.

Included with the canopy data is the USLE  $C$  factor, which is the ratio of loss to cropland under specific management conditions. The  $C$  factor is dependent on the canopy cover as well as management conditions, and therefore, the value may have to be adjusted for specific management conditions. The  $C$  factor included in the database is associated with maximum erosion decrease for the given crop cover or plant species, when compared to bare soil.

Finally, information is included on crop harvest variables. These variables include two harvest indices: one for optimal growth ( $HI_{opt}$ ), and the other for stressed growing conditions ( $HI_{min}$ ). The harvest index is the ratio of biomass harvested to the total aboveground biomass of the plant. Also included in the harvest variables is the nitrogen and phosphorus content in the yield ( $fr_{N, yld}$  and  $fr_{P, yld}$ ), which is used to determine the amount of nitrogen and phosphorus exported from the system.

## **Appendix D: Soil Characteristics for Pocomoke Watershed**

The tables below summarize descriptive information for each soil type and for each soil layer. SWAT includes information on the top 2 to 4 layers of soil depending on the soil layer depth. The top layer is considered to be most pertinent to the shallow rooted crop species. The summary information included in Table 39 lists the STATSGO code as well as the soil name, the number of soil layers associated with each soil type, the hydraulic group to which the soil type belongs, and the maximum rooting depth. The maximum rooting potential maximum depth defines the depth to which roots can extend as determined by the impermeability of specific soil layers and is not a function of the potential rooting depth of specific plant species. The hydrologic group is a classification scheme developed by the Natural Resource Conservation Service (NRCS) to describe runoff potential and cover conditions. Soils with the highest infiltration rates are classified as group A, while soils with the slowest infiltration rates are classified as soil group D.

**Table 39.** Summary information of each soil classification included in the Pocomoke watershed.

<b>STATSGO Code:</b>	<b>Soil Name:</b>	<b>Number of Layers:</b>	<b>NRCS Hydraulic Group:</b>	<b>Maximum Rooting Depth [mm]:</b>
DE001	EVESBORO	2	A	1524
DE009	POCOMOKE	4	B	1524
DE014	POCOMOKE	4	B	1524
MD003	WESTBROOK	3	D	2514
MD004	BIBB	2	D	1524
MD005	OTHELLO	4	C	1828
MD009	GALESTOWN	3	A	1651
MD040	FALLSINGTON	3	B	1828
MD041	POCOMOKE	4	B	1524
MD042	ELKTON	4	C	1651
MD054	CHINCOTEAGUE	3	D	1524
MD063	ROANOKE	4	D	1828
VA037	ROANOKE	4	D	1828
VA040	BOJAC	3	B	2159
VA046	CHINCOTEAGUE	3	D	1524

Table 40 through Table 43 list the clay, silt and sand content of each soil layer as well as the hydraulic conductivity, the available water content and the depth of each soil layer. SWAT includes summary information of up to four soil layers depended on the soil type.



**Table 40.** Summary soil information of first soil layer of each soil type.

STATSGO Code:	Soil Layer Depth [mm]:	Available Water Content [mm/mm]:	Hydraulic Conductivity [mm/hr]:	Percentage Clay [%]:	Percentage Silt [%]:	Percentage Sand [%]:
DE001	1016	0.10	500.00	2.00	16.41	81.59
DE009	254	0.18	54.00	12.50	41.86	45.64
DE014	254	0.17	120.00	12.50	19.65	67.85
MD003	254	0.35	350.00	10.00	45.00	45.00
MD004	305	0.17	19.00	10.00	57.09	32.91
MD005	228	0.21	1.70	21.50	67.29	11.21
MD009	279	0.09	290.00	7.00	9.07	83.93
MD040	254	0.12	100.00	11.50	23.11	65.39
MD041	254	0.18	54.00	12.50	41.86	45.64
MD042	254	0.13	76.00	15.50	18.98	65.52
MD054	152	0.24	2.00	22.50	67.96	9.54
MD063	178	0.13	52.00	14.00	19.90	66.10
VA037	178	0.12	65.00	14.00	19.90	66.10
VA040	203	0.14	300.00	5.50	30.58	63.92
VA046	152	0.24	2.60	22.50	67.96	9.54

**Table 41.** Summary soil information of second soil layer of each soil type.

STATSGO Code:	Soil Layer Depth [mm]:	Available Water Content [mm/mm]:	Hydraulic Conductivity [mm/hr]:	Percentage Clay [%]:	Percentage Silt [%]:	Percentage Sand [%]:
DE001	1524	0.11	2.00	47.50	2.78	49.72
DE009	711	0.13	64.00	11.50	23.11	65.39
DE014	711	0.13	64.00	11.50	23.11	65.39
MD003	1219	0.35	290.00	10.00	45.00	45.00
MD004	1524	0.10	83.00	10.00	23.44	66.56
MD005	736	0.20	0.85	27.50	65.34	7.16
MD009	1016	0.07	210.00	7.00	9.07	83.93
MD040	813	0.11	19.00	24.00	17.70	58.30
MD041	711	0.13	64.00	11.50	23.11	65.39
MD042	610	0.20	1.20	31.00	62.13	6.87
MD054	1016	0.22	0.77	27.50	65.34	7.16
MD063	305	0.16	5.50	27.50	37.82	34.68
VA037	305	0.16	7.90	27.50	37.82	34.68
VA040	1194	0.11	45.00	13.50	20.01	66.49
VA046	1016	0.22	1.10	27.50	65.34	7.16

**Table 42.** Summary soil information of third soil layer of each soil type.

STATSGO Code:	Soil Layer Depth [mm]:	Available Water Content [mm/mm]:	Hydraulic Conductivity [mm/hr]:	Percentage Clay [%]:	Percentage Silt [%]:	Percentage Sand [%]:
DE001	N/A	N/A	N/A	N/A	N/A	N/A
DE009	1016	0.08	130.00	7.50	9.02	83.48
DE014	1016	0.08	130.00	7.50	9.02	83.48
MD003	2515	0.19	3.50	18.50	54.40	27.10
MD004	N/A	N/A	N/A	N/A	N/A	N/A
MD005	1270	0.15	7.50	19.50	42.89	37.61
MD009	1651	0.03	550.00	4.00	1.49	94.51
MD040	1829	0.05	120.00	9.50	0.75	89.75
MD041	1016	0.08	130.00	7.50	9.02	83.48
MD042	1016	0.20	0.57	36.00	56.35	7.65
MD054	1524	0.04	110.00	9.50	0.75	89.75
MD063	1270	0.16	0.33	47.50	46.98	5.52
VA037	1270	0.19	0.53	47.50	46.98	5.52
VA040	2159	0.03	550.00	4.50	3.88	91.62
VA046	1524	0.04	130.00	9.50	0.75	89.75

**Table 43.** Summary soil information of fourth soil layer of each soil type.

STATSGO Code:	Soil Layer Depth [mm]:	Available Water Content [mm/mm]:	Hydraulic Conductivity [mm/hr]:	Percentage Clay [%]:	Percentage Silt [%]:	Percentage Sand [%]:
DE001	N/A	N/A	N/A	N/A	N/A	N/A
DE009	1524	0.10	13.00	20.50	18.45	61.05
DE014	1524	0.10	13.00	20.50	18.45	61.05
MD003	N/A	N/A	N/A	N/A	N/A	N/A
MD004	N/A	N/A	N/A	N/A	N/A	N/A
MD005	1829	0.07	190.00	7.00	9.07	83.93
MD009	N/A	N/A	N/A	N/A	N/A	N/A
MD040	N/A	N/A	N/A	N/A	N/A	N/A
MD041	1524	0.10	13.00	20.50	18.45	61.05
MD042	1651	0.13	22.00	17.50	23.07	59.43
MD054	N/A	N/A	N/A	N/A	N/A	N/A
MD063	1829	0.05	71.00	9.50	0.75	89.75
VA037	1829	0.05	89.00	9.50	0.75	89.75
VA040	N/A	N/A	N/A	N/A	N/A	N/A
VA046	N/A	N/A	N/A	N/A	N/A	N/A

## **Appendix E: Irrigation and Economic Model Variables and Values Used**

### *Irrigation Equipment and Water Costs:*

Table 44 summarizes the economic cost of the irrigation systems as used in this study. For demonstration purposes the economic component of the *IrrigEcon* application requires that a rough estimate of the cost of irrigation equipment, as well as the cost of construction, installation and maintenance be determined for use in this example project. In reality these costs are likely to vary greatly based upon the requirements of the fields, the specifications of the design, and the circumstances of the construction. The values presented in Table 44 are considered to be sample costs, and are used for the purposes of demonstration only; the costs presented in no way represent an actual cost estimate based upon a specific design.

Irrigation installation and construction costs must be determined based on the design specifications appropriate for each individual field. The values presented in Table 44 are intended to serve as an example in order to evaluate the performance and operation of *IrrigEcon* application. These costs are applied to all fields within the Pocomoke watershed as part of this study. Any individual wishing to determine the value of irrigation at a specific site must obtain irrigation installation and maintenance estimates that are appropriate for circumstances and the specific location under consideration. Once the irrigation system design or designs have been determined and the associated costs calculated, the relevant performance and economic data can be entered into a comma delineated text file in the format required by the *IrrigEcon* application. For an example of the required format see the `tbl_irrsys_GeneralData.txt` file included with the sample input files packaged with the *IrrigEcon* application software CD.

**Table 44.** Cost estimates for typical irrigation system installed in Maryland’s eastern shore for an average farm size of 170 acres.

<b>Irrigation System:</b>	<b>Installation Costs:</b>	<b>Annual Depreciation:</b>
Center Pivot <sup>38</sup>	8 Tower Pivot System <sup>39</sup>	\$55,000
	Well Pump and Generator	\$30,000
	Piping from Shallow Aquifer	\$7,500
	<b>Total:</b>	<b>\$92,500</b>
	Expected Life (20 years)	
	<b>Annual Capital Depreciation:</b>	<b>\$4,625</b>
Traveling Gun:	Well Pump and Generator	\$30,000
	Traveler Piping System	\$20,000
	<b>Total:</b>	<b>\$50,000</b>
	Expected Life (15 years)	
	<b>Annual Capital Depreciation:</b>	<b>\$3,350</b>
Drip Irrigation	Drip Laterals and Piping	\$50,000
	Well Pump and Generator	\$30,000
	Filter System	\$20,000
	<b>Total:</b>	<b>\$100,000</b>
	Expected Life (15 years)	
	<b>Annual Capital Depreciation:</b>	<b>\$6,700</b>

The price estimates quoted in Table 44 are based on an average farm size of 69 hectares (170 acres). The cost quoted is an estimate for parts, labor and installation, and reflects a rough estimate of the cost that the average farmer can expect to pay under present market conditions (i.e. the year 2005).

The system described above assumes that water is available from an aquifer accessible from the farm site, and the annual capital depreciation rate assumes the center

<sup>38</sup> Quotations are based on a personal communication (December 9, 2004) with Mr. Jim Fouks of Self Propelled Irrigation (410 673-7885), Preston MD.

<sup>39</sup> The referenced center pivot system is a high pressure system with drop heads. The system is estimated to be an eight tower system.

pivot irrigation system has a 20-year life; while both the drip system and traveling gun are expected to last 15 years. This information, as well as the calculated annual depreciation and maintenance cost is summarized in Table 45.

**Table 45.** Irrigation efficiency and installation, maintenance and operating costs.

<b>Irrigation System:</b>	<b>Installation Costs:</b>	<b>Annual Depreciation:</b>	<b>Annual Maintenance Costs:</b>	<b>Irrigation Efficiency:</b>
Drip Irrigation	\$100,000	\$6,700	\$2,000	0.95
Traveling Gun	\$50,000	\$3,350	\$2,000	0.80
Center Pivot	\$92,500	\$4,625	\$1,000	0.85

A survey of the available agricultural literature demonstrates both the range of the irrigation installation costs and the breadth of the irrigation design considerations to influence the cost of the system. Some of these estimates are presented below in support of the values used in this study. Buchanan and Cross (2002) with the University of Tennessee Agricultural Extension Service estimate the cost of drilling and installing a well system to be \$30,000 for a 30.5 cm (12-inch) diameter, 70 meters (200 feet) deep, 3,800 liters per minute (1000 gallon per minute) system. This is the same value assumed in this study for each of the systems considered.

Paetz and Maloney (2002), consultants with Cascade Earth Sciences (CES), estimated the cost of a center pivot system used to irrigate a total of 40 hectares (100 acres), to be \$112,500, in addition to an average monthly maintenance cost of \$500 dollars during the growing season. The values used in this study, \$92,500 for a 69 hectare (170 acre system) and \$1,000 in annual maintenance cost, is lower than the projected cost by Paetz and Maloney (2002). However, Bress (2003), with the University of Missouri Outreach and Extension, reports alternative estimates, determined by annual

survey of irrigated corn producers, that are almost identical to the values used in this study. Bress reports equipment annual depreciation cost of \$26 per acre (\$4,420 for 170 acres), and annual maintenance costs of \$5.50 per acre (\$935 for 170 acres). These values very closely match the values used in this study which equate to an annual depreciation cost of \$4,625 and maintenance costs of \$1,000 per year.

Paetz and Maloney (2002) estimated the cost of traveler units to range from \$25,000 to \$35,000 with an additional maintenance cost of \$2,500 to \$5,000. The estimated monthly maintenance cost varies depending on the labor required to move the system. A value of \$20,000 dollars is used for the cost of the traveler and piping, and an annual maintenance cost of \$2,000 is assumed, which greatly underestimate the frequency or labor required to move the system during irrigation events based on the estimates of Paetz and Maloney.

In the case of drip irrigation, the Washington State University Extension (2004) estimated the cost of installing a drip irrigation system for growing hops to be \$1000 per acre (\$2,500 per hectare). The design system assumed by the Washington State University Extension is expected to last 21 years, with an additional annual maintenance cost of \$15 per acre (\$37 per hectare). The values used in this study underestimate the combined cost by approximately \$1,800 per year. The costs used in this study assume a total cost of \$100,000 for a 170 acre system, but assume a shorter expected life of 15 years. The assumed annual maintenance cost used in this study is \$2,000 compared to roughly \$2,500 assuming \$15 per acre for 170 acres.

The installation and maintenance costs presented in Table 44 and Table 45 represent values based on the rough estimates of a single irrigation contractor, and

therefore could vary from supplier to supplier, and may change with shifting market prices. Therefore, alternative cost estimates from other supplier sources and installation contractors may significantly change the recommendations obtained in this study. The conclusions made in this study are, therefore, based solely on economic cost parameters used during the operation of the irrigation-economic model.

Moreover, the approach is not limited to objectively comparing three distinct irrigation systems: traveling gun, center pivot and drip irrigation, as done in this study. Rather, the methodology can be applied to a single system (center pivot for example), where multiple cost estimates can be obtained, each varying in the materials used, the efficiency of the design, the maintenance requirements and the expected life of the system. The end result will be the computation of the overall net benefit associated with each system, where the system with the greatest net benefit (or the most economically optimal) is the recommended system.

It should be noted that alternative construction designs and materials used will not only affect water use efficiency and the installation cost, but may alter the expected life of the system, as well as the salvage value and maintenance cost of the system, all of which is taken into consideration by the model. The obvious outcome and advantage to this approach is the selection of the most economically favorable system design.

For the purposes of this demonstration, three distinct systems are being compared, and it is assumed that each is equally feasible and that the only selection criteria is economic, although this often may not be the case. Factors other than installation cost and irrigation water use efficiency often determine the type of system that is most appropriate. For example, considering the case of melon production, or other crop

species that are potentially sensitive to fungal growth, it may be found that drip irrigation is the favored system, due to the negative effects of overhead irrigation in contributing to the promotion of fungal disease. However, drip irrigation may not be the most effective system for a densely grown crop such as wheat due to the sowing and harvesting techniques employed. The decision support system incorporated into this model makes irrigation system recommendations based on economic factors alone, and assumes other production factors and procedures are unaffected by the irrigation. Therefore, it is imperative that the user of the *IrrigEcon* application input or select only the associated data for the irrigation system that are feasible and selected for consideration.

#### *Cost of Water:*

An important cost variable not included in the breakdown above is the cost of water itself, which is estimated at a basic rate of 3 cents/m<sup>3</sup> of water. This estimate reflects the cost of pumping the water from shallow groundwater supplies, but does not include the cost of the pumping equipment itself, already included in the cost estimates of the irrigation system installation above, nor does it include the cost of any additional tariffs imposed by the state. The estimate is calculated using equation 92 (Pair et al., 1969), assuming a pumping efficiency of 70%, a pumping flow rate of 100 L/s, a total dynamic head of 40 m, and an average cost of electricity of 0.000823 \$/kWH. Essentially this value represents the cost of delivery, required to deliver the water from groundwater supplies to the field. However, it does not take into account a value for the water itself.



$$PkW = \frac{Q \cdot tdh}{101.9} \quad (95)$$

Where,  $PkW$  is the power output [kW],  $P_r$  is the pumping rate or discharge [L/sec], and  $tdh$  is the total dynamic head [m].

Using the assumptions included in the above example calculation a water cost level of 3 cents/m<sup>3</sup> is determined. Based on this calculation a water cost of 3 cents/m<sup>3</sup> is considered the lower limit for the range of possible water cost levels. This calculation assumes that water is obtained from an on site source and does not have the additional cost that may be associated with an off-site source or municipal water source. For comparison purposes a spectrum of possible water cost levels is applied in this study ranging from a hypothetical cost of 0 cents/m<sup>3</sup> to an upper limit of 25 cents/m<sup>3</sup>. A range of values is considered in order to simulate competitive pricing for limited water supplies or regulatory pricing imposed by the state or governmental authority for the promotion of water conservation measures.

The upper water cost level of 25 cents/m<sup>3</sup> is chosen based on the findings of a comprehensive report on the economic values of freshwater throughout the United States (Frederick et al., 1996), calculated in 1994 dollars. This report estimates the value of water for various uses throughout the United States based on an economic model of supply and demand. The report estimates the value of irrigation water for the Mid-Atlantic region at \$198 per acre-foot (roughly 16 cents/m<sup>3</sup>). This value, coupled with the cost of deliver and inflation is estimated at 25 cents/m<sup>3</sup>, which is the value used in this study.

*Agricultural Production Costs:*

In the irrigation-economic model agricultural production/operating costs are applied as the basic input cost for determining the net benefit value of agriculture with and without irrigation. The average annual operation cost determined here is on a per hectare basis, and is considered the basic cost of operating the farm and includes the cost of agricultural inputs such as seed, fertilizer, lime, pesticides, petroleum fuel and oil, as well as service items such as repair and maintenance of capital items, machine hire, contract labor, marketing, storage and transportation. The net operating cost is determined by summing all agricultural costs as reported by MASS (2004) and subtracting the net governmental payments, which may serve to alleviate the cost of running the farm, and dividing by the total farmland acreage. This sort of broad analysis yields a rough estimate for an average farm operating in Maryland.

The capital and maintenance cost of irrigation equipment and water is added to the above-mentioned operating costs in simulations where irrigation is applied. The production cost estimates are based on Maryland agricultural statistical data provided by MASS for the year 2003 and may vary from year to year, however, the values are considered to be a reasonable estimate of actual operating costs.

This statistical information does not, however, distinguish between the variable operating costs of different crops, but rather sums the costs of all agricultural crops for a given year. It is understood that certain crops will require higher inputs in order to achieve acceptable yields, while other crops may require fewer inputs and therefore have lower operating costs associated with them. Nevertheless, if the average farm operating cost for all farmland, determined on a per hectare basis, is used for all agricultural crops

included in this model then it is assumed that much of the error associated with the insufficient operating cost information will cancel each other when the crop simulations are viewed in proper proportion to the percentage of agricultural land devoted to the production of each crop species, as reported by the MASS.

Table 46 reports the total cost for all farmlands within Maryland for each of the categories of costs listed below (MASS, 2004) for the year 2003. Give the total agricultural cropland area of 833,650 hectares (2,060,000 acres) in the state of Maryland, the average operating cost for each hectare of farmland is estimated to be 330 \$/ha.

**Table 46.** Operating Cost of all Agricultural Farms within Maryland.

<b>Cost Item:</b>	<b>Cost for 2003 [Thousand Dollars]:</b>
Seed Purchased	83,039
Fertilizer and Lime	44,161
Pesticides	37,464
Petroleum Fuel and Oils	42,581
Machine Hire and Custom Work	16,106
Marketing, Storage, and Transportation	61,857
Contract Labor	12,269
Net Government Transactions	-20,302
<b>Total:</b>	<b>277,715</b>

*SWAT Variables Used in the Irrigation-Economic Model:*

The economic-irrigation model draws values from both the input and output files of the SWAT model. Table 47 list the pertinent variables used by *IrrigEcon* application and the source file from which the value is obtained.

**Table 47.** SWAT variables incorporated into the irrigation economic model.

<b>Variable:</b>	<b>Variable Description:</b>	<b>Source File:</b>
LULC	Four letter character code for the cover/plant on the HRU	crop.dat
HRU	Hydrologic response unit number	.sbs
AREA	Drainage area of the HRU (km <sup>2</sup> ).	.sbs
IRR	Irrigation (mm H <sub>2</sub> O). Amount of irrigation water applied to HRU during time step.	.sbs
PET	Potential evapotranspiration (mm H <sub>2</sub> O). Potential evapotranspiration from the HRU during the time step.	.sbs
ET	Actual evapotranspiration (soil evaporation and plant transpiration) from the HRU during the time step (mm H <sub>2</sub> O).	.sbs
SW	Soil water content (mm H <sub>2</sub> O). Amount of water in the soil profile at the end of the time period.	.sbs
PRECIP	Total amount of precipitation falling during time step (mm H <sub>2</sub> O).	.sbs
SURQ	Surface runoff contribution to stream flow (mm H <sub>2</sub> O)	.sbs
REVAP	Return flow to the root zone from the shallow aquifer (mm H <sub>2</sub> O)	.sbs
PERC	Water that percolates past the root zone during the time step (mm H <sub>2</sub> O). There is usually a lag between the time the water leaves the bottom of the root zone and reaches the shallow aquifer. Over a long period of time, this variable should equal groundwater recharge (PERC=GW_RCHG as time approaches infinity).	.sbs
YLD	Harvested yield (metric tons/ha). The model partitions yields from the total biomass on a daily basis (and reports it). However, the actual yield is not known until it is harvested.	.sbs

## Appendix F: Irrigation Economic Decision Support Program Code

The following Visual Basic ® is included for reference purposes and contains the programming code used to obtain the net benefit and irrigation water demand values reported in this document.

```
Option Explicit
```

```
'Declaration of Variables:
'File/System Variables
Public sSwatFileName As String
Public sSwatFileName100Irr As String
Public sTempSwatDataFile As String
Public sTempSwatDataFile100Irr As String
Public sEconInternalFileName As String
Public sIrrInternalFileName As String
Public iMsgVariable As Integer
Public sSelectIrrSys As String 'variable used to set the selected
    'irrigation system used in Net Benefit Calculations if applicable

'AGRR-SWAT data Array
Public sTotAreaAgrrWat As Single 'represents the total area of AGRR
    'land in the watershed [km]
Public sAvgAreaAgrrHRU As Single 'represents the average area of all
    'AGRR HRU within the simulations [km]
Public iHruHigh As Integer 'highest Hru number in Swat data array
Public iSubHigh As Integer 'highest Sub number in Swat data array
Public iHruCount As Integer 'total number of HRU's of in the
    'watershed.
Public iMoCount As Integer 'the total number of months being modeled
    '(it counts the average for the year data as one month)

'All of the following Array variables are contained within
'the SWAT .sbs Output file
Public iSwatArraySize As Long 'ArraySize or number of records with
    'AGRR as the LULC
Private lAgrrCtr() As Long      '[]
Private sLulc() As String * 4
Private iHru() As Integer      '[]
Private iGis() As Integer      '[]
Private iSub() As Integer      '[]
Private iMgt() As Integer      '[]
Private iMon() As Integer      '[]
Private sArea() As Single      '[km^2]
Private sPrecip() As Single     '[mm of H2O]
Private sSnoFall() As Single    '[mm of H2O]
Private sSnoMelt() As Single    '[mm of H2O]
Private sIrr() As Single        '[mm of H2O]
Private sPet() As Single        '[mm of H2O]
```

```

Private sAEt() As Single      '[mm of H2O]
Private sSw() As Single      '[mm of H2O]
Private sPerc() As Single    '[mm of H2O]
Private sGwRchg() As Single  '[mm of H2O]
Private sDaRchg() As Single  '[mm of H2O]
Private sRevap() As Single   '[mm of H2O]
Private sSaIrr() As Single   '[mm of H2O]
Private sDaIrr() As Single   '[mm of H2O]
Private sSaSt() As Single    '[mm of H2O]
Private sDaSt() As Single    '[mm of H2O]
Private sSurq() As Single    '[mm of H2O]
Private sTLoss() As Single   '[mm of H2O]
Private sLatq() As Single    '[mm of H2O]
Private sGwQ() As Single     '[mm of H2O]
Private sWYld() As Single    '[mm of H2O]
Private sSYld() As Single    '[metric tons/ha]
Private sUslc() As Single    '[metric tons/ha]
Private sAppP() As Single    '[kg P/ha]
Private sAppNA() As Single   '[kg N/ha]
Private sUtoPA() As Single   '[kg P/ha]
Private sUto() As Single     '[kg N/ha]
Private sNgrz() As Single    '[kg N/ha]
Private sPgrz() As Single    '[kg P/ha]
Private sAin() As Single     '[kg N/ha]
Private sNfix() As Single    '[kg N/ha]
Private sFMn() As Single     '[kg N/ha]
Private sAMn() As Single     '[kg N/ha]
Private sASn() As Single     '[kg N/ha]
Private sFMp() As Single     '[kg P/ha]
Private sNameNum() As Single '[ ]
Private sLAP() As Single     '[kg P/ha]
Private sASP() As Single     '[kg P/ha]
Private sDNit() As Single    '[kg P/ha]
Private sNUP() As Single     '[kg N/ha]
Private sPUP() As Single     '[kg P/ha]
Private sORGN() As Single    '[kg N/ha]
Private sORGP() As Single    '[kg P/ha]
Private sSEDP() As Single    '[kg P/ha]
Private sURQ() As Single     '[kg N/ha]
Private sATQ() As Single     '[ ]
Private sNO3() As Single     '[kg N/ha]
Private s3GW() As Single     '[ ]
Private sSOLP() As Single    '[kg P/ha]
Private sPGW() As Single     '[kg P/ha]
Private sWSTRS() As Single   '[days]
Private sTMP_STRS() As Single '[days]
Private sN_STRS() As Single   '[days]
Private sP_STRS() As Single   '[days]
Private sBIOM() As Single    '[metric tons/ha]
Private sLAI() As Single     '[ ]
Private sYLD() As Single     '[metric tons/ha]
Private sBACTP() As Single   '[count]
Private sBACTLP() As Single  '[count]

Private iETDif() As Integer  '[mm of H2O]
Private sTimeStepYld() As Single 'converts the actual Year to date
                                'yield to the yield for the specific time step.

```

```

Private sTimeStepCalcPotentialYld() As Single 'potential yield
        'calculated for each HRU
Private sTimeStepCalcActYld() As Single
        'the actual yield without irrigation Calculated using the
        'Deficit Irrigation Equation
Private sTimeStepCalcPotentialYld2() As Single 'from the revised
        'equation.
Private sTimeStepCalcActYld2() As Single 'from the revised equation.

'the following variables are taken from the SWAT .sbs simulation
'with irrigation.
Private sAEtMax() As Single
Private iETDiffMax() As Single
Private sIrrMax() As Single
Private sYldMax() As Single
Private sTimeStepYldMax() As Single
Private sSwatIrrEff() As Single
Private sTimeStepPotentialYld() As Single

'The following Variables are Calculated during the Net Benefit
'Iterations corresponding to each AGRR SWAT record stored in the
'Array variables above and for each Irrigation system.
Private sAppliedIrrSys() As String
Private sOptIrrDepth() As Single
Private sOptIrrVol() As Single
Private sMaxNetBenefitWI() As Single
Private sMaxNetBenefitWOI() As Single
Private sMaxNetBenefitDif() As Single
Private sOptActIrrYld() As Single
Private sOptActIrrET() As Single

'The following are needed in the Net Benefit Calculations:
'The final value of each is assigned to these variables.
Private sTargetET() As Single
Private sIrrDepth() As Single
Private sIrrVol() As Single
Private sNetBenefit() As Single
Private sNetBenefitWOI() As Single
Private sYldDivisor() As Single 'values written to file to varify
        'calculations
Private sProdCost() As Single 'values written to file to varify
        'calculations
Private sRevenue() As Single 'values written to file to varify
        'calculations
Private sWaterCost() As Single 'values written to file to varify
        'calculations
Private sTargetYld() As Single 'maximum target yield less than
        'potential yld.
Private sRatioTetPet() As Single
Private sRatioTetMet() As Single

'The following Variables are Included in summary tables for each Hru.
Public iNumHru As Integer 'the number of AGrr HRU's in the
        'SWAT data array
Private iHruHruSum() As Integer
Private iSubHruSum() As Integer
Private sAvgIrrDHruMo() As Single

```

```

Private sAvgIrrDHruYr() As Single
Private sAvgIrrVHruMo() As Single
Private sAvgIrrVHruYr() As Single
Private sAvgIrrNBWIHruMo() As Single
Private sAvgIrrNBWIHruYr() As Single
Private sAvgIrrNBWOIHruMo() As Single
Private sAvgIrrNBWOIHruYr() As Single
Private sAvgIrrNBDifHruYr() As Single 'The difference between the
    'NB with and without irrigation
Private sAvgIrrRecHruYr() As Boolean 'set as true if the irrigation
    'system brings additional NB for the year

```

'The following Variables are used solely for the purpose of  
'determining which Irrigation system to use.

```

Private sCPivotNBWOIYr() As Single
Private sCPivotNBWIYr() As Single
Private sCPivotNBDifYr() As Single
Private bCPivotRecYr() As Boolean 'set as true if the irrigation
    'system brings additional NB for the year
Private sTGunNBWOIYr() As Single
Private sTGunNBWIYr() As Single
Private sTGunNBDifYr() As Single
Private bTGunRecYr() As Boolean 'set as true if the irrigation
    'system brings additional NB for the year
Private sDripNBWOIYr() As Single
Private sDripNBWIYr() As Single
Private sDripNBDifYr() As Single
Private bDripRecYr() As Boolean 'set as true if the irrigation
    'system brings additional NB for the year
Private sRecIrrSys() As String
Private sTotIrrVolSubYr() As Single
Private iRecIrrSysInt() As Integer
Private sCPivotIrrVolYr() As Single
Private sTGunIrrVolYr() As Single
Private sDripIrrVolYr() As Single
Private sNBMaxDif() As Single

```

'The following Variables are Included in summary tables for each  
Subbasin.

```

Public iNumSub As Long 'the number of Subbassins in the data array
Private iSubSubSum() As Integer
Private sAvgIrrDSubMo() As Single
Private sAvgIrrDSubYr() As Single
Private sAvgIrrVSubMo() As Single
Private sAvgIrrVSubYr() As Single
Private sAvgIrrNBWISubMo() As Single
Private sAvgIrrNBWISubYr() As Single
Private sAvgIrrNBWOISubMo() As Single
Private sAvgIrrNBWOISubYr() As Single

```

'The following Variables are Included in summary tables for the entire  
watershed.

```

Private sAvgIrrDWatMo As Single
Private sAvgIrrDWatYr As Single
Private sAvgIrrVWatMo As Single
Private sAvgIrrVWatYr As Single
Private sAvgIrrNBWIWatMo As Single

```



```
Private sAvgIrrNBWIWatYr As Single
Private sAvgIrrNBWOIWatMo As Single
Private sAvgIrrNBWOIWatYr As Single
```

'The following Variables are Included in the monthly summary tables for each Hru.

```
Public iMoNumHru As Integer 'holds the size of this array group
Private iMoHruHruSum() As Integer
Private iMoSubHruSum() As Integer
Private iMoMonHruSum() As Integer
Private sMoAvgIrrDHruMo() As Single
Private sMoAvgIrrVHruMo() As Single
Private sMoAvgNBWIHruMo() As Single
Private sMoAvgNBWOIHruMo() As Single
```

'The following Variables are Included in the monthly summary tables for each Subbasin.

```
Public iMoNumSub As Integer 'holds the size of this array group
Private iMoSubSubSum() As Integer
Private iMoMonSubSum() As Integer
Private sMoAvgIrrDSubMo() As Single
Private sMoAvgIrrVSubMo() As Single
Private sMoAvgNBWISubMo() As Single
Private sMoAvgNBWOISubMo() As Single
```

'The following Variables are Included in monthly summary tables for the entire watershed.

```
Private iMoMonWatMo(11) As Integer
Private sMoAvgIrrDWatMo(11) As Single
Private sMoAvgIrrVWatMo(11) As Single
Private sMoAvgNBWIWatMo(11) As Single
Private sMoAvgNBWOIWatMo(11) As Single
```

'The following is a list of Economic Variables Needed for the execution of the program

```
Public iEconArraySize As Integer
Private sEconIdCrop(15) As String * 4
Private sEconDescription(15) As String
Private sEconKy(15) As Single
Private sEconPCrop(15) As Single
Private sEconCVar(15) As Single
Private sEconCFix(15) As Single
Private sEconCComb(15) As Single
Private sEconCWater(15) As Single
Private sEconKc(15) As Single
```

'The following is a list of Irrigation System Variables Needed for the execution of the program

```
Public iIrrigArraySize As Integer
Private sIrrSys(3) As String 'Abbreviation code for system
Private sIrrDescription(3) As String 'Full name description of system
Private sIrrInstall(3) As Single 'Total installation cost for the
'irrigation system base on 170 ha area of coverage [$/farm]
Private sInst_ha(3) As Single 'Calculated: Average installation
'cost on hectare basis [$/ha]
Private sAnnDep(3) As Single 'Calculated: Annual depreciation
'based on expected life of the system per ha [$/ha/yr]
```

```

Private sAnnMain(3) As Single      'Total annual maintenance cost
    'for the system [$/yr]
Private sAnnMain_ha(3) As Single  'Calculated: Annual maintenance
    'cost on a hectare basis [$/ha/yr]
Private sSalValue(3) As Single    'Expected Salvage cost at the
    'end of the expected life of the system [$/ha]
Private sIrrEff(3) As Single      'Irrigation efficiency []
Private sExpLife(3) As Single     'Expected life of the system [yr]
Private sIrrSysArea(3) As Single  'Average farm area assumed for
    'the predicted farm area [ha]
Private sMonDep(3) As Single      'Calculated: Monthly
    'deprecitation [$/ha/mo]
Private sMonMain_ha(3) As Single  'Calculated: Monthly
    'Maintenance Cost [$/ha/mo]

```

'The following procedure executes all calculation procedures without user initiation.

```

Private Sub cmdFullRun_Click()
    Call cmdSwatSelect_Click
    Call cmdNB_All_Click
    Call cmdRecommendations_Click
    Call cmdIrrVol_Click
End Sub

```

'STEP 1: Primary call procedures  
'Code Required for Selecting and Loading Input File Data.

```

'Selects ECONOMIC input data file
Public Sub cmdEconSelect_Click()
    Dim sSelectFile As String
    Dim sEconOutputFile As String
    Dim sTitlePhrase As String

    sTitlePhrase = "Select Economic Input Data File."
    sSelectFile = SelectFile(sTitlePhrase)
    sEconOutputFile = App.Path & "\TempFiles\tbl_econ.txt"
    sEconInternalFileName = App.Path & "\TempFiles\tbl_econ.txt"
    Call CreateInternalFile(sSelectFile, sEconOutputFile)
End Sub

```

```

'STEP 1: Primary call procedures
'Selects IRRIGATION input data file
Public Sub cmdIrrSelect_Click()
    Dim sSelectFile As String
    Dim sIrrOutputFile As String
    Dim sTitlePhrase As String

    sTitlePhrase = "Select Irrigation Input Data File."
    sSelectFile = SelectFile(sTitlePhrase)
    sIrrOutputFile = App.Path & "\TempFiles\tbl_irrsys.txt"
    sIrrInternalFileName = App.Path & "\TempFiles\tbl_irrsys.txt"
    Call CreateInternalFile(sSelectFile, sIrrOutputFile)
End Sub

```

'STEP 1: Primary call procedures

```

'Selects SWAT input data file
Public Sub cmdSwatSelect_Click()
    Dim sSelectFile As String
    Dim sSelectFileMax As String
    Dim iMsgVariable As Integer
    Dim sTitlePhrase As String

    sTitlePhrase = "Select First SWAT .sbs (1) Input Data File."
    sSelectFile = SelectFile(sTitlePhrase)
    sTitlePhrase = "Select Second SWAT .sbs (2) Input Data File."
    sSelectFileMax = SelectFile(sTitlePhrase)
    sTempSwatDataFile = App.Path & "\TempFiles\TempSwatDataFile.txt"
    sTempSwatDataFile100Irr = App.Path &
"\TempFiles\TempSwatDataFile_100Irr.txt"
    sSwatFileName = sTempSwatDataFile
    sSwatFileName100Irr = sTempSwatDataFile100Irr

    Call FormatSwatFile(sSelectFile)
    Call FormatSwatFileMax(sSelectFileMax)
    iMsgVariable = MsgBox("SWAT Variables Have Been Loaded", vbOKOnly,
"Program Status Message")
End Sub

```

```

'Step 1: 2nd level Support Procedures
'The following function 'Triggers the Open File Dialog Box.
Public Function SelectFile(sTitlePhrase As String) As String
    cdbFile.DialogTitle = sTitlePhrase
    cdbFile.ShowOpen
    SelectFile = cdbFile.FileName
End Function

```

```

'Step 1: 2nd level Support Procedures
'The procedure CreateInternalFile copies the selected file to a temp
internal data file
Public Sub CreateInternalFile(sSelectFile As String, _
    sInternalFileName As String)
    Dim sFileLines() As String
    Dim sTempLineInput As String
    Dim lctr As Long
    Dim i As Long
    Dim j As Integer
    Dim lFileLength As Long
    Dim iHeaderLines As Integer 'counts the number of lines in the
header if any.

```

```

    lFileLength = DataFileLength(sSelectFile)
    lctr = 0

```

```

    Open sSelectFile For Input As #1
    ReDim sFileLines(0 To lFileLength)

```

```

'Do loop loads input data into a temporary array
Do While (EOF(1) = False)
    Line Input #1, sFileLines(lctr)
    lctr = lctr + 1

```

```

Loop
Close #1
lctr = lctr - 1

'For loop eliminates extra tabs and converts to comma separated.
For i = 0 To lctr
    Call FindReplace(sFileLines(i), Chr(9), ",", lctr)
Next i

For j = 0 To 3
    For i = 0 To lctr
        Call FindReplace(sFileLines(i), ",", ", ", lctr)
    Next i
Next j

'For loop writes temp file
Open sInternalFileName For Output As #1
For i = 0 To lctr
    Call PrintDataFile(sFileLines(i))
Next i
Close
End Sub

'Step 1: 2nd level Support Procedures
'This function reformats the data if the .sbs file was exported from
ArcView.
Public Sub FormatSwatFile(sSelectFile As String)
    Dim sFileLines() As String
    Dim sTempLineInput As String
    Dim lctr As Long
    Dim i As Long
    Dim lFileLength As Long
    Dim iHeaderLines As Integer 'counts the number of lines
                                'in the header if any.

    lFileLength = DataFileLength(sSelectFile)
    lctr = 0
    iHeaderLines = 0

    Open sSelectFile For Input As #1

    'The following loop eliminates any material ahead of the
    ' actual data that may be contained within the file.
    sTempLineInput = "Initiation of Line Input Variable"
    Do While (Left(sTempLineInput, 4) <> "LULC")
        Line Input #1, sTempLineInput
        iHeaderLines = iHeaderLines + 1
    Loop

    lFileLength = lFileLength - iHeaderLines
    ReDim sFileLines(0 To lFileLength)

    Do While (EOF(1) = False)
        Line Input #1, sFileLines(lctr)
        lctr = lctr + 1
    Loop
    Close #1

```

```

lctr = lctr - 1

'The following codes creates a temp file of SWAT data.
Open sTempSwatDataFile For Output As #1
Print #1,
"LULC,HRU,GIS,SUB,MGT,MON,AREAk2,PRECIPmm,SNOFALLmm,SNOMELTmm,IRRmm,PE
Tmm,ETmm,SWmm,PERCmm,GWRCHGmm,DARCHGmm,REVAPmm,SAIRRmm,DAIRRmm,SASTmm,D
ASTmm,SURQmm,TLOSSmm,LATQmm,GWQmm,WYLDmm,SYLDt/ha,USLEt/ha,NAPPkg/ha,PA
PPkg/ha,NAUTOkg/ha,PAUTOkg/ha,NGRZkg/ha,PGRZkg/ha,NRAINkg/ha,NFIXkg/ha,
F-MNkg/ha,A-MNkg/ha,A-SNkg/ha,F-MPkg/ha,AO-LPkg/ha,L-APkg/ha,A-
SPkg/ha,DNITkg/ha,NUPkg/ha,PUPkg/ha,ORGNkg/ha,ORGPkg/ha,SEDPkg/ha,NSURQ
kg/ha,NLATQkg/ha,NO3Lkg/ha,NO3GWkg/ha,SOLPkg/ha,PGWkg/ha,WSTRS,TMPSTRS,
NSTRS,PSTRS,BIOMt/ha,LAI,YLDt/ha,BACTPct,BACTLPct,"

'The following if statement test for the two .sbs file types.
If Mid(sFileLines(0), 5, 1) = Chr(9) Then
    'IF this is true the data file is exported from ArcView and
    'is tab delineated.
    For i = 0 To lctr
        Call FindReplace(sFileLines(i), Chr(9), ",", lctr)
        Call PrintDataFile(sFileLines(i))
    Next i
Else
    For i = 0 To lctr
        Call FormatBasinSwatLine(sFileLines(i))
    Next i
End If
Close #1
sSwatFileName = sTempSwatDataFile
End Sub

'Step 1: 2nd level Support Procedures
Public Sub FormatSwatFileMax(sSelectFile As String)
    'This function reformats the data if the .sbs file was exported
    'from ArcView, if it was not but was rather taken from the
    'basins.sbs file then another formate prodecure is needed
    'as there are no tabs included in this file.
    Dim sFileLines() As String
    Dim sTempLineInput As String
    Dim lctr As Long
    Dim i As Long
    Dim lFileLength As Long
    Dim iHeaderLines As Integer 'counts the number of lines in the
    'header if any.

    lFileLength = DataFileLength(sSelectFile)
    lctr = 0
    iHeaderLines = 0

    Open sSelectFile For Input As #1

    'The following loop eliminates any material ahead of the actual
    data that may be contained within the file.
    sTempLineInput = "Initiation of Line Input Variable"
    Do While (Left(sTempLineInput, 4) <> "LULC")
        Line Input #1, sTempLineInput
        iHeaderLines = iHeaderLines + 1
    
```

```

Loop

lFileLength = lFileLength - iHeaderLines
ReDim sFileLines(0 To lFileLength)

Do While (EOF(1) = False)
    Line Input #1, sFileLines(lctr)
    lctr = lctr + 1
Loop
Close #1
lctr = lctr - 1

Open sTempSwatDataFile100Irr For Output As #1
Print #1,
"LULC,HRU,GIS,SUB,MGT,MON,AREAKm2,PRECIPmm,SNOFALLmm,SNOMELTmm,IRRmm,PE
Tmm,ETmm,SWmm,PERCmm,GWRCHGmm,DARCHGmm,REVAPmm,SAIRRmm,DAIRRmm,SASTmm,D
ASTmm,SURQmm,TLOSSmm,LATQmm,GWQmm,WYLDmm,SYLDt/ha,USLEt/ha,NAPPkg/ha,PA
PPkg/ha,NAUTOkg/ha,PAUTOkg/ha,NGRZkg/ha,PGRZkg/ha,NRAINkg/ha,NFIXkg/ha,
F-MNkg/ha,A-MNkg/ha,A-SNkg/ha,F-MPkg/ha,AO-LPkg/ha,L-APkg/ha,A-
SPkg/ha,DNITkg/ha,NUPkg/ha,PUPkg/ha,ORGNkg/ha,ORGPkg/ha,SEDPkg/ha,NSURQ
kg/ha,NLATQkg/ha,NO3Lkg/ha,NO3GWkg/ha,SOLPkg/ha,PGWkg/ha,WSTRS,TMPSTRS,
NSTRS,PSTRS,BIOMt/ha,LAI,YLDt/ha,BACTPct,BACTLPct,"

'The following if statement test for the two .sbs file types.
If Mid(sFileLines(0), 5, 1) = Chr(9) Then
    'IF this is true the data file is exported from ArcView and
    'is tab delineated.
    For i = 0 To lctr
        Call FindReplace(sFileLines(i), Chr(9), ",", lctr)
        Call PrintDataFile(sFileLines(i))
    Next i
Else
    For i = 0 To lctr
        Call FormatBasinSwatLine(sFileLines(i))
    Next i
End If
Close #1
sSwatFileName100Irr = sTempSwatDataFile100Irr
End Sub

'Step 1: 3rd Level Support Procedures
'Function determines the number of lines within an input file.
Public Function DataFileLength(sFileName As String) As Long
    Dim lctr As Long
    Dim sLineRecord As String

    lctr = 0
    Open sFileName For Input As #1
    Do While (EOF(1) = False)
        Line Input #1, sLineRecord
        lctr = lctr + 1
    Loop
    Close #1
    lctr = lctr + 1
    DataFileLength = lctr
End Function

```

```

'Step 1: 3rd Level Support Procedures
'Function replaces data in a search string
Public Sub FindReplace(ByRef sSearchString As String, _
    ByVal sFindWhat$, ByVal sReplaceWith$, lctr As Long)
    Dim i As Long 'counter for loop control
    Dim iPos As Integer, iStart As Integer

    iStart% = 1
    Do
        For i = 0 To lctr
            'Find beginning position
            iPos% = InStr(iStart%, sSearchString, sFindWhat$)
            'If not there, then get out
            If iPos% = 0 Then Exit Do
            'Combine left portion, new string, and right portion
            sSearchString = Left(sSearchString, iPos% - 1) & sReplaceWith$
& _
                Right(sSearchString, Len(sSearchString) - iPos% -
Len(sFindWhat$) + 1)
            'Calculate where to begin next search
            iStart% = iPos% + Len(sReplaceWith$)
            Next i
        Loop
    End Sub

'Step 1: 3rd Level Support Procedures
Public Sub PrintDataFile(sSwatFileLine As String)
    Print #1, sSwatFileLine
End Sub

'Step 1: 3rd Level Support Procedures
Public Sub FormatBasinSwatLine(sLine As String)
    Dim sTabFormattedFileLine As String
    Dim v1 As String
    Dim v2, v3, v4, v5, v6 As Integer
    Dim v7, v8, v9, v10, v11, v12, v13, v14, v15, v16, v17, v18, v19, _
        v20, v21, v22, v23, v24, v25, v26, v27, v28, v29, v30, v31, _
        v32, v33, v34, v35, v36, v37, v38, v39, v40, v41, v42, v43, _
        v44, v45, v46, v47, v48, v49, v50, v51, v52, v53, v54, v55, _
        v56, v57, v58, v59, v60, v61, v62, v63, v64, v65 As Single

    v1 = LTrim(Left(sLine, 4))
    v2 = LTrim(Mid(sLine, 5, 4))
    v3 = LTrim(Mid(sLine, 10, 8))
    v4 = LTrim(Mid(sLine, 19, 4))
    v5 = LTrim(Mid(sLine, 24, 4))
    v6 = LTrim(Mid(sLine, 29, 4))
    v7 = LTrim(Mid(sLine, 33, 10))
    v8 = LTrim(Mid(sLine, 43, 10))
    v9 = LTrim(Mid(sLine, 53, 10))
    v10 = LTrim(Mid(sLine, 63, 10))
    v11 = LTrim(Mid(sLine, 73, 10))
    v12 = LTrim(Mid(sLine, 83, 10))
    v13 = LTrim(Mid(sLine, 93, 10))
    v14 = LTrim(Mid(sLine, 103, 10))
    v15 = LTrim(Mid(sLine, 113, 10))

```

```

v16 = LTrim(Mid(sLine, 123, 10))
v17 = LTrim(Mid(sLine, 133, 10))
v18 = LTrim(Mid(sLine, 143, 10))
v19 = LTrim(Mid(sLine, 153, 10))
v20 = LTrim(Mid(sLine, 163, 10))
v21 = LTrim(Mid(sLine, 173, 10))
v22 = LTrim(Mid(sLine, 183, 10))
v23 = LTrim(Mid(sLine, 193, 10))
v24 = LTrim(Mid(sLine, 203, 10))
v25 = LTrim(Mid(sLine, 213, 10))
v26 = LTrim(Mid(sLine, 223, 10))
v27 = LTrim(Mid(sLine, 233, 10))
v28 = LTrim(Mid(sLine, 243, 10))
v29 = LTrim(Mid(sLine, 253, 10))
v30 = LTrim(Mid(sLine, 263, 10))
v31 = LTrim(Mid(sLine, 273, 10))
v32 = LTrim(Mid(sLine, 283, 10))
v33 = LTrim(Mid(sLine, 293, 10))
v34 = LTrim(Mid(sLine, 303, 10))
v35 = LTrim(Mid(sLine, 313, 10))
v36 = LTrim(Mid(sLine, 323, 10))
v37 = LTrim(Mid(sLine, 333, 10))
v38 = LTrim(Mid(sLine, 343, 10))
v39 = LTrim(Mid(sLine, 353, 10))
v40 = LTrim(Mid(sLine, 363, 10))
v41 = LTrim(Mid(sLine, 373, 10))
v42 = LTrim(Mid(sLine, 383, 10))
v43 = LTrim(Mid(sLine, 393, 10))
v44 = LTrim(Mid(sLine, 403, 10))
v45 = LTrim(Mid(sLine, 413, 10))
v46 = LTrim(Mid(sLine, 423, 10))
v47 = LTrim(Mid(sLine, 433, 10))
v48 = LTrim(Mid(sLine, 443, 10))
v49 = LTrim(Mid(sLine, 453, 10))
v50 = LTrim(Mid(sLine, 463, 10))
v51 = LTrim(Mid(sLine, 473, 10))
v52 = LTrim(Mid(sLine, 483, 10))
v53 = LTrim(Mid(sLine, 493, 10))
v54 = LTrim(Mid(sLine, 503, 10))
v55 = LTrim(Mid(sLine, 513, 10))
v56 = LTrim(Mid(sLine, 523, 10))
v57 = LTrim(Mid(sLine, 533, 10))
v58 = LTrim(Mid(sLine, 543, 10))
v59 = LTrim(Mid(sLine, 553, 10))
v60 = LTrim(Mid(sLine, 563, 10))
v61 = LTrim(Mid(sLine, 573, 10))
v62 = LTrim(Mid(sLine, 583, 10))
v63 = LTrim(Mid(sLine, 593, 10))
v64 = LTrim(Mid(sLine, 603, 10))
v65 = LTrim(Mid(sLine, 613, 10))

```

'the following line prints to the TempSWATFile

```
If v1 = "AGRR" Then
```

```
Print #1, v1 & "," & Chr(9) & v2 & "," & Chr(9) & v3 & "," & _
    & Chr(9) & v4 & "," & Chr(9) & v5 & "," & Chr(9) & v6 & _
    "," & Chr(9) & v7 & "," & Chr(9) & v8 & "," & Chr(9) & v9 & _
    "," & Chr(9) & v10 & "," & Chr(9) & v11 & "," & Chr(9) & _
```



```

v12 & "," & Chr(9) & v13 & "," & Chr(9) & v14 & "," & _
Chr(9) & v15 & ","; Chr(9) & v16 & "," & Chr(9) & v17 & _
"," & Chr(9) & v18 & "," & Chr(9) & v19 & "," & Chr(9) & _
v20 & "," & Chr(9) & v21 & "," & Chr(9) & v22 & "," & _
Chr(9) & v23 & "," & Chr(9) & v24 & "," & Chr(9) & v25 & _
"," & Chr(9) & v26 & "," & Chr(9) & v27 & "," & Chr(9) & _
v28 & "," & Chr(9) & v29 & "," & Chr(9) & v30 & "," & _
Chr(9) & v31 & "," & Chr(9) & v32 & "," & Chr(9) & v33 & _
"," & Chr(9) & v34 & "," & Chr(9) & v35 & "," & Chr(9) & _
v36 & "," & Chr(9) & v37 & "," & Chr(9) & v38 & "," & Chr(9) & _
Chr(9) & v39 & "," & Chr(9) & v40 & "," & Chr(9) & v41 & _
"," & Chr(9) & v42 & "," & Chr(9) & v43 & "," & Chr(9) & _
v44 & "," & Chr(9) & v45 & "," & Chr(9) & v46 & "," & _
Chr(9) & v47 & "," & Chr(9) & v48 & "," & Chr(9) & v49 & _
"," & Chr(9) & v50 & "," & Chr(9) & v51 & "," & Chr(9) & _
v52 & "," & Chr(9) & v53 & "," & Chr(9) & v54 & "," & _
Chr(9) & v55 & "," & Chr(9) & v56 & "," & Chr(9) & v57 & _
"," & Chr(9) & v58 & "," & Chr(9) & v59 & "," & Chr(9) & _
v60 & "," & Chr(9) & v61 & "," & Chr(9) & v62 & "," & _
Chr(9) & v63 & "," & Chr(9) & v64 & "," & Chr(9) & v65
Else: End If

```

End Sub

```

'STEP 2: Primary call procedures
'Code Required for Viewing Input File Data.

```

```

Private Sub cmdViewSwatData_Click()
Load frmSwatData
frmSwatData.Show
End Sub

```

```

Private Sub cmdViewEconData_Click()
Load frmEconData
frmEconData.Show
End Sub

```

```

Private Sub cmdViewIrrigData_Click()
Load frmIrrigData
frmIrrigData.Show
End Sub

```

```

'STEP 3: Primary call procedures
'Code Required for Running Net Benefit Calculations

```

```

Private Sub cmdNB_1_Click()
Dim iIrrType As Integer 'Selects the type of irrigation system
Dim i As Integer 'integer counter

sSelectIrrSys = "irr_cpivot"
iIrrType = 0
Call InitiateNBCalc(iIrrType)
Call CompareNB_IrrSys

```

```

        Call CalcOptimalIrrVol
        Close
    End Sub

'STEP 3: Primary call procedures
Private Sub cmdNB_2_Click()
    Dim iIrrType As Integer 'Selects the type of irrigation system
    Dim i As Integer 'integer counter

    sSelectIrrSys = "irr_tgun"
    iIrrType = 1
    Call InitiateNBCalc(iIrrType)
    Call CompareNB IrrSys
    Call CalcOptimalIrrVol
    Close
End Sub

'STEP 3: Primary call procedures
Private Sub cmdNB_3_Click()
    Dim iIrrType As Integer 'Selects the type of irrigation system
    Dim i As Integer 'integer counter

    sSelectIrrSys = "irr_drip"
    iIrrType = 2
    Call InitiateNBCalc(iIrrType)
    Call CompareNB IrrSys
    Call CalcOptimalIrrVol
    Close
End Sub

'STEP 3: Primary call procedures
Private Sub cmdNB_All_Click()
    Dim iNBCalc As Integer

    iNBCalc = 10
    Call InitiateNBCalc(iNBCalc)
    Call CompareNB IrrSys
    Call CalcOptimalIrrVol
    Close
End Sub

'STEP 3: Primary call procedures
'Procedure runs all NB calculations without user prompting
Private Sub cmdRunCalc_Click()
    Call cmdNB_All_Click
    Call CompareNB IrrSys
    Call CalcOptimalIrrVol
    Close
End Sub

'STEP 3: 2nd Level support procedures
Public Sub InitiateNBCalc(iIrrType As Integer)

    'Loads Econ data variables into variable array from econ data file
    Call LoadEconVariables

```

```

'Loads Irrig data variables into variable array from irrsys data
file
Call LoadIrrigVariables
'Loads Swat Variables into variable array from data files
Call LoadSwatVariables
'Loads Swat Variables running Swat with 100 irrigation.
Call LoadSwatVariablesMax
'Calculates values and writes to data file.
Call CalculateNetBenefit(iIrrType)
End Sub

```

```
'STEP 3: 3rd Level support procedures
```

```
Public Sub LoadEconVariables()
```

```

Dim iCtr As Integer
Dim sEconIdCropTemp As String * 4
Dim sEconDescriptionTemp As String
Dim sEconKyTemp As Single
Dim sEconPCropTemp As Single
Dim sEconCVarTemp As Single
Dim sEconCFixTemp As Single
Dim sEconCCombTemp As Single
Dim sEconCWaterTemp As Single
Dim sEconColHeadings As String
Dim sEconKcTemp As Single

```

```
sEconInternalFileName = App.Path & "\TempFiles\tbl_econ.txt"
```

```
Open sEconInternalFileName For Input As #1
```

```
Line Input #1, sEconColHeadings
```

```
iCtr = 0
```

```
Do While (EOF(1) = False)
```

```

Input #1, sEconIdCropTemp, sEconDescriptionTemp, sEconKyTemp, _
sEconPCropTemp, sEconCVarTemp, sEconCFixTemp, _
sEconCCombTemp, sEconCWaterTemp, sEconKcTemp

```

```

sEconIdCrop(iCtr) = sEconIdCropTemp
sEconDescription(iCtr) = sEconDescriptionTemp
sEconKy(iCtr) = sEconKyTemp
sEconPCrop(iCtr) = sEconPCropTemp
sEconCVar(iCtr) = sEconCVarTemp
sEconCFix(iCtr) = sEconCFixTemp
sEconCComb(iCtr) = sEconCCombTemp
sEconCWater(iCtr) = sEconCWaterTemp
sEconKc(iCtr) = sEconKcTemp

```

```
iCtr = iCtr + 1
```

```
Loop
```

```
Close #1
```

```
Close #2
```

```
iEconArraySize = iCtr
```

```
End Sub
```

```
'STEP 3: 3rd Level support procedures
```

```
Public Sub LoadIrrigVariables()
```

```

Dim iCtr As Integer
Dim sIrrSysTemp As String
Dim sIrrDescriptionTemp As String
Dim sIrrInstallTemp As Single
Dim sInst_haTemp As Single
Dim sAnnDepTemp As Single
Dim sAnnMainTemp As Single
Dim sAnnMain_haTemp As Single
Dim sSalValueTemp As Single
Dim sIrrEffTemp As Single
Dim sExpLifeTemp As Single
Dim sIrrSysAreaTemp As Single
Dim sIrrColHeadings As String
Dim sMonDepTemp As Single
Dim sMonMain_haTemp As Single

sIrrInternalFileName = App.Path & "\TempFiles\tbl_irrsys.txt"
Open sIrrInternalFileName For Input As #1
Line Input #1, sIrrColHeadings
iCtr = 0

Do While (EOF(1) = False)
    Input #1, sIrrSysTemp, sIrrDescriptionTemp, sIrrInstallTemp, _
        sAnnMainTemp, sSalValueTemp, sIrrEffTemp, sExpLifeTemp, _
        sIrrSysAreaTemp

    sInst_haTemp = sIrrInstallTemp / sIrrSysAreaTemp
    sAnnDepTemp = sInst_haTemp / sExpLifeTemp
    sAnnMain_haTemp = sAnnMainTemp / sExpLifeTemp
    sMonDepTemp = sAnnDepTemp / 12
    sMonMain_haTemp = sAnnMain_haTemp / 12

    sIrrSys(iCtr) = sIrrSysTemp
    sIrrDescription(iCtr) = sIrrDescriptionTemp
    sIrrInstall(iCtr) = sIrrInstallTemp
    sInst_ha(iCtr) = sInst_haTemp
    sAnnDep(iCtr) = sAnnDepTemp
    sAnnMain(iCtr) = sAnnMainTemp
    sAnnMain_ha(iCtr) = sAnnMain_haTemp
    sSalValue(iCtr) = sSalValueTemp
    sIrrEff(iCtr) = sIrrEffTemp
    sExpLife(iCtr) = sExpLifeTemp
    sIrrSysArea(iCtr) = sIrrSysAreaTemp
    sMonDep(iCtr) = sMonDepTemp
    sMonMain_ha(iCtr) = sMonMain_haTemp

    iCtr = iCtr + 1
Loop

Close #1

iIrrigArraySize = iCtr
End Sub

'STEP 3: 3rd Level support procedures
Public Sub LoadSwatVariables()

```

```

'Variables used in the LoadSwatVariables Subroutine.
Dim iAgrrCount As Long 'Counts the number of Records with LULC of
AGRR
Dim lRecordCount As Long 'Counts the number of Records in SWAT file
                          '(all records)

Dim iArraySize As Long
Dim iNBVarArraySize As Long
Dim lctr As Long
Dim iMsgVariable As Integer
Dim sLulcTemp As String
Dim iHruTemp, iGisTemp, iSubTemp, iMgtTemp, iMonTemp As Integer
Dim i7, i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19, _
    i20, i21, i22, i23, i24, i25, i26, i27, i28, i29, i30, i31, _
    i32, i33, i34, i35, i36, i37, i38, i39, i40, i41, i42, i43, _
    i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55, _
    i56, i57, i58, i59, i60, i61, i62, i63, i64, i65 As Single
Dim i As Long 'for counter
Dim lSwatCtr As Long
Dim bHruCountComplete As Boolean
Dim sHeaderLine As String

iAgrrCount = 0
lRecordCount = 0
sLulcTemp = "temp"
bHruCountComplete = False

iHruCount = 1
iMoCount = 1

iArraySize = DataFileLength(sSwatFileName)
iIrrigArraySize = DataFileLength(sIrrInternalFileName)

Call ReDimSwatArray(iArraySize)
Call ReDimNBVariables(iArraySize)

Open sSwatFileName For Input As #1
Line Input #1, sHeaderLine

Do While (EOF(1) = False)
Input #1, sLulcTemp, iHruTemp, iGisTemp, iSubTemp, iMgtTemp, _
    iMonTemp, i7, i8, i9, i10, i11, i12, i13, i14, i15, _
    i16, i17, i18, i19, i20, i21, i22, i23, i24, i25, _
    i26, i27, i28, i29, i30, i31, i32, i33, i34, i35, _
    i36, i37, i38, i39, i40, i41, i42, i43, i44, i45, _
    i46, i47, i48, i49, i50, i51, i52, i53, i54, i55, _
    i56, i57, i58, i59, i60, i61, i62, i63, i64, i65

    If sLulcTemp = "AGRR" Then
        lctr = iAgrrCount
        lAgrrCtr(lctr) = lctr
        sLulc(lctr) = sLulcTemp
        iHru(lctr) = iHruTemp
        iGis(lctr) = iGisTemp
        iSub(lctr) = iSubTemp
        iMgt(lctr) = iMgtTemp
        iMon(lctr) = iMonTemp
        sArea(lctr) = i7
    End If

```

sPrecip(lctr) = i8  
sSnoFall(lctr) = i9  
sSnoMelt(lctr) = i10  
sIrr(lctr) = i11  
sPet(lctr) = i12  
sAEt(lctr) = i13  
sSw(lctr) = i14  
sPerc(lctr) = i15  
sGwRchg(lctr) = i16  
sDaRchg(lctr) = i17  
sRevap(lctr) = i18  
sSaIrr(lctr) = i19  
sDaIrr(lctr) = i20  
sSaSt(lctr) = i21  
sDaSt(lctr) = i22  
sSurq(lctr) = i23  
sTLoss(lctr) = i24  
sLatq(lctr) = i25  
sGwQ(lctr) = i26  
sWYld(lctr) = i27  
sSYld(lctr) = i28  
sUsle(lctr) = i29  
sAppP(lctr) = i30  
sAppNA(lctr) = i31  
sUtoPA(lctr) = i32  
sUto(lctr) = i33  
sNgrz(lctr) = i34  
sPgrz(lctr) = i35  
sAin(lctr) = i36  
sNfix(lctr) = i37  
sFMn(lctr) = i38  
sAMn(lctr) = i39  
sASn(lctr) = i40  
sFMp(lctr) = i41  
sNameNum(lctr) = i42  
sLAP(lctr) = i43  
sASP(lctr) = i44  
sDNit(lctr) = i45  
sNUP(lctr) = i46  
sPUP(lctr) = i47  
sORGN(lctr) = i48  
sORGP(lctr) = i49  
sSEDP(lctr) = i50  
sURQ(lctr) = i51  
sATQ(lctr) = i52  
sNO3(lctr) = i53  
s3GW(lctr) = i54  
sSOLP(lctr) = i55  
sPGW(lctr) = i56  
sWSTRS(lctr) = i57  
sTMP\_STRS(lctr) = i58  
sN\_STRS(lctr) = i59  
sP\_STRS(lctr) = i60  
sBIOM(lctr) = i61  
sLAI(lctr) = i62  
sYLD(lctr) = i63  
sBACTP(lctr) = i64

```

        sBACTLP(lctr) = i65

        iETDif(lctr) = sPet(lctr) - sAEt(lctr)

        iAgrrCount = iAgrrCount + 1
        lRecordCount = lRecordCount + 1

    Else:
        lRecordCount = lRecordCount + 1
    End If

If lctr <> 0 Then
    If (iHru(lctr) > iHru(lctr - 1)) And (iMoCount = 1) Then
        iHruCount = iHruCount + 1
    Else: bHruCountComplete = True
    End If

    If (iHru(lctr) < iHru(lctr - 1)) Then
        iMoCount = iMoCount + 1
    Else: End If
Else: End If
Loop
Close #1 'closes Temp SWAT input txt file

sAvgAreaAgrrHRU = sTotAreaAgrrWat / iHruCount

iAgrrCount = iAgrrCount - 1
iSwatArraySize = iAgrrCount

'Sets the sTimeStepYld values
For i = 0 To (iSwatArraySize - 177)
    lSwatCtr = i
    'The following if-then-else statement is intended to change the
    reported yld in Swat (the year to date or up to the timestep) to the
    yield for that specific timestep
    If (iMon(i + 177) < 13) And sYLD(i + 177) > sYLD(i) Then
        sTimeStepYld(i) = sYLD(i + 177) - sYLD(i)
    Else:
        If iMon(i + 177) < 13 Then
            sTimeStepYld(i) = 0
        Else: sTimeStepYld(i) = sYLD(i)
        End If
    End If
Next i

If iMon(i) > 12 Then
    sTimeStepYld(i) = sYLD(i)
Else: End If
Next i

For i = (iSwatArraySize - 176) To iSwatArraySize
    sTimeStepYld(i) = sYLD(i)
Next i
End Sub

'STEP 3: 3rd Level support procedures
Public Sub LoadSwatVariablesMax()
    'Variables used in the LoadSwatVariables Subroutine.

```

```

    Dim iAgrrCount As Long 'Counts the number of Records with LULC of
AGRR
    Dim lRecordCount As Long 'Counts the number of Records in SWAT file
(all records)
    Dim iArraySize As Long
    Dim iNBVarArraySize As Long
    Dim lctr As Long
    Dim iMsgVariable As Integer
    Dim sLulcTemp As String
    Dim iHruTemp, iGisTemp, iSubTemp, iMgtTemp, iMonTemp As Integer
    Dim i7, i8, i9, i10, i11, i12, i13, i14, i15, i16, i17, i18, i19, _
        i20, i21, i22, i23, i24, i25, i26, i27, i28, i29, i30, i31, _
        i32, i33, i34, i35, i36, i37, i38, i39, i40, i41, i42, i43, _
        i44, i45, i46, i47, i48, i49, i50, i51, i52, i53, i54, i55, _
        i56, i57, i58, i59, i60, i61, i62, i63, i64, i65 As Single
    Dim i As Long 'for counter
    Dim lSwatCtr As Long
    Dim bHruCountComplete As Boolean
    Dim sHeaderLine As String

    iAgrrCount = 0
    lRecordCount = 0
    sLulcTemp = "temp"
    bHruCountComplete = False

    iHruCount = 1
    iMoCount = 1

    iArraySize = DataFileLength(sSwatFileName)
    iIrrigArraySize = DataFileLength(sIrrInternalFileName)

    Open sSwatFileName100Irr For Input As #1
    Line Input #1, sHeaderLine

    Do While (EOF(1) = False)
    Input #1, sLulcTemp, iHruTemp, iGisTemp, iSubTemp, iMgtTemp, _
        iMonTemp, i7, i8, i9, i10, i11, i12, i13, i14, i15, i16, _
        i17, i18, i19, i20, i21, i22, i23, i24, i25, i26, i27, i28, _
        i29, i30, i31, i32, i33, i34, i35, i36, i37, i38, i39, i40, _
        i41, i42, i43, i44, i45, i46, i47, i48, i49, i50, i51, i52, _
        i53, i54, i55, i56, i57, i58, i59, i60, i61, i62, i63, i64, i65
    If sLulcTemp = "AGRR" Then
        lctr = iAgrrCount
        lAgrrCtr(lctr) = lctr
        sIrrMax(lctr) = i11
        sAETMax(lctr) = i13
        sYldMax(lctr) = i63

        iETDiffMax(lctr) = sAETMax(lctr) - sAET(lctr)

        If (sIrrMax(lctr) <> 0) And (sAET(lctr) <> sAETMax(lctr))
Then
            sSwatIrrEff(lctr) = (sAETMax(lctr) - sAET(lctr)) /
sIrrMax(lctr)
        Else:
            sSwatIrrEff(lctr) = 1
        End If
    
```



```

        iAgrrCount = iAgrrCount + 1
        lRecordCount = lRecordCount + 1

    Else:
        lRecordCount = lRecordCount + 1
    End If
Loop
Close #1 'closes Temp SWAT input txt file

iAgrrCount = iAgrrCount - 1
iSwatArraySize = iAgrrCount

'Sets the sTimeStepYld values
For i = 0 To (iSwatArraySize - 177)
    lSwatCtr = i
    'The following if-then-else statement is intended to change the
    reported yld in Swat (the year to date or up to the timestep) to the
    yield for that specific timestep
    If (iMon(i + 177) < 13) And sYldMax(i + 177) > sYldMax(i) Then
        sTimeStepYldMax(i) = sYldMax(i + 177) - sYldMax(i)
    Else:
        If iMon(i + 177) < 13 Then
            sTimeStepYldMax(i) = 0
        Else: sTimeStepYldMax(i) = sYldMax(i)
        End If
    End If

    If iMon(i) > 12 Then
        sTimeStepYldMax(i) = sYldMax(i)
    Else: End If
Next i

For i = (iSwatArraySize - 176) To iSwatArraySize
    sTimeStepYldMax(i) = sYldMax(i)
Next i
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub ReDimSwatArray(iArraySize As Long)
    'Swat Variables read from the Swat simulation with no irrigation
    applied.
    ReDim lAgrrCtr(iArraySize) As Long
    ReDim sLulc(iArraySize) As String * 4
    ReDim iHru(iArraySize) As Integer
    ReDim iGis(iArraySize) As Integer
    ReDim iSub(iArraySize) As Integer
    ReDim iMgt(iArraySize) As Integer
    ReDim iMon(iArraySize) As Integer
    ReDim sArea(iArraySize) As Single
    ReDim sPrecip(iArraySize) As Single
    ReDim sSnoFall(iArraySize) As Single
    ReDim sSnoMelt(iArraySize) As Single
    ReDim sIrr(iArraySize) As Single
    ReDim sPet(iArraySize) As Single
    ReDim sAEt(iArraySize) As Single

```

```

ReDim sSw(iArraySize) As Single
ReDim sPerc(iArraySize) As Single
ReDim sGwRchg(iArraySize) As Single
ReDim sDaRchg(iArraySize) As Single
ReDim sRevap(iArraySize) As Single
ReDim sSaIrr(iArraySize) As Single
ReDim sDaIrr(iArraySize) As Single
ReDim sSaSt(iArraySize) As Single
ReDim sDaSt(iArraySize) As Single
ReDim sSurq(iArraySize) As Single
ReDim sTLoss(iArraySize) As Single
ReDim sLatq(iArraySize) As Single
ReDim sGwQ(iArraySize) As Single
ReDim sWYld(iArraySize) As Single
ReDim sSYld(iArraySize) As Single
ReDim sUsle(iArraySize) As Single
ReDim sAppP(iArraySize) As Single
ReDim sAppNA(iArraySize) As Single
ReDim sUtoPA(iArraySize) As Single
ReDim sUto(iArraySize) As Single
ReDim sNgrz(iArraySize) As Single
ReDim sPgrz(iArraySize) As Single
ReDim sAin(iArraySize) As Single
ReDim sNfix(iArraySize) As Single
ReDim sFMn(iArraySize) As Single
ReDim sAMn(iArraySize) As Single
ReDim sASn(iArraySize) As Single
ReDim sFMp(iArraySize) As Single
ReDim sNameNum(iArraySize) As Single
ReDim sLAP(iArraySize) As Single
ReDim sASP(iArraySize) As Single
ReDim sDNit(iArraySize) As Single
ReDim sNUP(iArraySize) As Single
ReDim sPUP(iArraySize) As Single
ReDim sORGN(iArraySize) As Single
ReDim sORGP(iArraySize) As Single
ReDim sSEDP(iArraySize) As Single
ReDim sURQ(iArraySize) As Single
ReDim sATQ(iArraySize) As Single
ReDim sNO3(iArraySize) As Single
ReDim s3GW(iArraySize) As Single
ReDim sSOLP(iArraySize) As Single
ReDim sPGW(iArraySize) As Single
ReDim sWSTRS(iArraySize) As Single
ReDim sTMP_STRS(iArraySize) As Single
ReDim sN_STRS(iArraySize) As Single
ReDim sP_STRS(iArraySize) As Single
ReDim sBIOM(iArraySize) As Single
ReDim sLAI(iArraySize) As Single
ReDim sYLD(iArraySize) As Single
ReDim sBACTP(iArraySize) As Single
ReDim sBACTLP(iArraySize) As Single
ReDim iETDif(iArraySize) As Integer

'Variables read from Swat Simulation with irrigation
ReDim sAEtMax(iArraySize) As Single
ReDim sIrrMax(iArraySize) As Single

```

```

    ReDim sYldMax(iArraySize) As Single
    ReDim sTimeStepYldMax(iArraySize) As Single
    ReDim sSwatIrrEff(iArraySize) As Single
    ReDim iETDiffMax(iArraySize) As Single
    ReDim sTimeStepPotentialYield(iArraySize) As Single
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub ReDimNBVariables(iArraySize As Long)
    ReDim sAppliedIrrSys(iArraySize * 3) As String
    ReDim sTargetET(iArraySize * 3) As Single
    ReDim sIrrDepth(iArraySize * 3) As Single
    ReDim sIrrVol(iArraySize * 3) As Single
    ReDim sNetBenefit(iArraySize * 3) As Single
    ReDim sNetBenefitWOI(iArraySize * 3) As Single
    ReDim sYldDivisor(iArraySize * 3) As Single
    ReDim sProdCost(iArraySize * 3) As Single
    ReDim sRevenue(iArraySize * 3) As Single
    ReDim sWaterCost(iArraySize * 3) As Single
    ReDim sTargetYld(iArraySize * 3) As Single
    ReDim sTimeStepCalcPotentialYld(iArraySize * 3) As Single
    ReDim sTimeStepCalcActYld(iArraySize * 3) As Single
    ReDim sTimeStepCalcPotentialYld2(iArraySize * 3) As Single
    ReDim sTimeStepCalcActYld2(iArraySize * 3) As Single
    ReDim sRatioTetPet(iArraySize * 3) As Single
    ReDim sRatioTetMet(iArraySize * 3) As Single
    ReDim sTimeStepYld(iArraySize * 3) As Single

    'Corresponding Net Benefit Variables listed below.
    ReDim sOptIrrDepth(iArraySize * 3) As Single
    ReDim sOptIrrVol(iArraySize * 3) As Single
    ReDim sMaxNetBenefitWI(iArraySize * 3) As Single
    ReDim sMaxNetBenefitWOI(iArraySize * 3) As Single
    ReDim sMaxNetBenefitDif(iArraySize * 3) As Single
    ReDim sOptActIrrYld(iArraySize * 3) As Single
    ReDim sOptActIrrET(iArraySize * 3) As Single
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub ReDimNBRecVariables()
    'ReDims Values used in determining Best Irrigation System
    ReDim sCPivotNBWOIYr(iNumHru * 3) As Single
    ReDim sCPivotNBWIIYr(iNumHru * 3) As Single
    ReDim sCPivotNBDifYr(iNumHru * 3) As Single
    ReDim bCPivotRecYr(iNumHru * 3) As Boolean
    ReDim sTGunNBWOIYr(iNumHru * 3) As Single
    ReDim sTGunNBWIIYr(iNumHru * 3) As Single
    ReDim sTGunNBDifYr(iNumHru * 3) As Single
    ReDim bTGunRecYr(iNumHru * 3) As Boolean
    ReDim sDripNBWOIYr(iNumHru * 3) As Single
    ReDim sDripNBWIIYr(iNumHru * 3) As Single
    ReDim sDripNBDifYr(iNumHru * 3) As Single
    ReDim bDripRecYr(iNumHru * 3) As Boolean
    ReDim sRecIrrSys(iNumHru * 3) As String
    ReDim sTotIrrVolSubYr(iNumHru * 3) As Single
    ReDim iRecIrrSysInt(iNumHru * 3) As Integer
    ReDim sCPivotIrrVolYr(iNumHru * 3) As Single

```

```

    ReDim sTGunIrrVolYr(iNumHru * 3) As Single
    ReDim sDripIrrVolYr(iNumHru * 3) As Single
    ReDim sNBMaxDif(iNumHru * 3) As Single
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub ReDimHruSummary()
    Dim i As Long
    Dim iNumMoHruValues As Integer

    iNumHru = 1
    sTotAreaAgrrWat = sArea(0)
    For i = 1 To iSwatArraySize
        If iHru(i) > iHru(i - 1) Then
            iHruHigh = iHru(i)
            iNumHru = iNumHru + 1
            sTotAreaAgrrWat = sTotAreaAgrrWat + sArea(i)
        Else: Exit For
        End If
    Next i
    iNumMoHruValues = iNumHru * 12

    'ReDims the General Summary Tables.
    ReDim iHruHruSum(iNumHru) As Integer
    ReDim iSubHruSum(iNumHru) As Integer
    ReDim sAvgIrrDHruMo(iNumHru) As Single
    ReDim sAvgIrrDHruYr(iNumHru) As Single
    ReDim sAvgIrrVHruMo(iNumHru) As Single
    ReDim sAvgIrrVHruYr(iNumHru) As Single
    ReDim sAvgIrrNBWIHruMo(iNumHru) As Single
    ReDim sAvgIrrNBWIHruYr(iNumHru) As Single
    ReDim sAvgIrrNBWOIHruMo(iNumHru) As Single
    ReDim sAvgIrrNBWOIHruYr(iNumHru) As Single
    ReDim sAvgIrrNBDifHruYr(iNumHru) As Single
    ReDim sAvgIrrRecHruYr(iNumHru) As Boolean

    'ReDims the Monthly Summary Tables.
    ReDim iMoHruHruSum(iNumMoHruValues) As Integer
    ReDim iMoSubHruSum(iNumMoHruValues) As Integer
    ReDim iMoMonHruSum(iNumMoHruValues) As Integer
    ReDim sMoAvgIrrDHruMo(iNumMoHruValues) As Single
    ReDim sMoAvgIrrDHruYr(iNumMoHruValues) As Single
    ReDim sMoAvgIrrVHruMo(iNumMoHruValues) As Single
    ReDim sMoAvgIrrVHruYr(iNumMoHruValues) As Single
    ReDim sMoAvgNBWIHruMo(iNumMoHruValues) As Single
    ReDim sMoAvgNBWOIHruMo(iNumMoHruValues) As Single
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub ReDimSubSummary()
    Dim i As Long
    Dim iNumMoSubValues As Long

    iNumSub = 0
    For i = 1 To iSwatArraySize
        If iSub(i) > iSub(i - 1) Then
            iSubHigh = iSub(i)
        End If
    Next i
End Sub

```

```

        iNumSub = iNumSub + 1
    Else: End If
Next i
iNumMoSubValues = iNumSub * 12

'ReDims the general summary arrays for each subbasin.
ReDim iHruSubSum(iSubHigh) As Integer
ReDim iSubSubSum(iSubHigh) As Integer
ReDim sAvgIrrDSubMo(iSubHigh) As Single
ReDim sAvgIrrDSubYr(iSubHigh) As Single
ReDim sAvgIrrVSubMo(iSubHigh) As Single
ReDim sAvgIrrVSubYr(iSubHigh) As Single
ReDim sAvgIrrNBWISubMo(iSubHigh) As Single
ReDim sAvgIrrNBWISubYr(iSubHigh) As Single
ReDim sAvgIrrNBWOISubMo(iSubHigh) As Single
ReDim sAvgIrrNBWOISubYr(iSubHigh) As Single

'ReDims the Monthly summary arrays for each subbasin.
ReDim iMoHruSubSum(iNumMoSubValues) As Integer
ReDim iMoSubSubSum(iNumMoSubValues) As Integer
ReDim iMoMonSubSum(iNumMoSubValues) As Integer
ReDim sMoAvgIrrDSubMo(iNumMoSubValues) As Single
ReDim sMoAvgIrrDSubYr(iNumMoSubValues) As Single
ReDim sMoAvgIrrVSubMo(iNumMoSubValues) As Single
ReDim sMoAvgIrrVSubYr(iNumMoSubValues) As Single
ReDim sMoAvgNBWISubMo(iNumMoSubValues) As Single
ReDim sMoAvgNBWOISubMo(iNumMoSubValues) As Single
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub CalculateNetBenefit(iIrrType As Integer)
    'General Counter variables used below
    Dim iIrrCtr As Integer 'counter for Irrig array variables
    Dim i As Long 'Loop counter for printing of yield comparison at end
of routine
    Dim j As Integer 'counter for the number of irrigation system
records

    Call OpenGenOutPutPrintFiles

    If iIrrType = 10 Then
        For j = 0 To 2
            iIrrCtr = j
            Call OpenNBPrintFiles(iIrrCtr)
            Call RunNBCalculations(iIrrCtr)
            Call CloseNBPrintFiles
        Next j
        Close
    Else: iIrrCtr = iIrrType
        Call OpenNBPrintFiles(iIrrCtr)
        Call RunNBCalculations(iIrrCtr)
        Call CloseNBPrintFiles
        Close
    End If

```

```

    'This routine checks that the actual yield calculated by SWAT is
    equal to the yield calculated assuming no irrigation

    Open App.Path & "\\ModelOutputFiles\100_CheckActualYields.txt" For
    Output As #100
    Print #100, "The yield reported in the first column is the yield
    reported by SWAT with no Irrigation"
    Print #100, "The yield reported in the second and third column is
    the yield calculated using the deficit irrigation equation using the
    max yield as that reported by SWAT with 100% irrigation."
    Print #100,
    Print #100,
    Print #100, "ActSWATYld", "CalcActYld", "CalcActYld2", _
    "MaxSWATYld", "CalcPotYld", "CalcPotYld2", "sAET", "sAETMax"

    For i = 0 To iSwatArraySize
    Print #100, sTimeStepYld(i), sTimeStepCalcActYld(i), _
    sTimeStepCalcActYld2(i), sTimeStepYldMax(i), _
    sTimeStepCalcPotentialYld(i), sTimeStepCalcPotentialYld2(i), _
    sAET(i), sAETMax(i)
    Next i
    Close #100
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub OpenGenInputPrintFiles()
    Dim sTempLineInput As String

    Open App.Path & "\\ModelOutputFiles\21_TempNBDataFile.txt" For Input
    As #21
    Line Input #21, sTempLineInput
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub OpenGenOutPutPrintFiles()
    Open App.Path & "\\ModelOutputFiles\21_TempNBDataFile.txt" For
    Output As #21
    Print #21, "IrrCtr", "HRU", "Irr_Sys", "Avg.Yr.NB.WOI", _
    "Avg.Yr.NB.WI", "Avg.Yr.NB.Dif.", "Avg.Yr.IrrV"

    Open App.Path & "\\ModelOutputFiles\20_NBCalcTempFile.txt" For
    Output As #20
    Print #20, "HRU", "NBCPWI", "NBCPWOI", "NBCPDif", "NBTGWI",
    "NBTGWOI", "NBTGDif", "NBDripWI", "NBDripWOI", "NBDripDif"

    'The following opens the files to be written to during the course
    of the calculations.
    Open App.Path & "\\ModelOutputFiles\01_TargetETEgVariables.txt" For
    Output As #1
    Open App.Path & "\\ModelOutputFiles\02_IrrVolEqVariables.txt" For
    Output As #2
    Open App.Path & "\\ModelOutputFiles\03_NetBenefitEqVariables.txt"
    For Output As #3
    Open App.Path & "\\ModelOutputFiles\04_zModelTestResults.txt" For
    Output As #4
    Open App.Path & "\\ModelOutputFiles\05_NetBenefitEqVariablesAbb.txt"
    For Output As #5

```

```
Open App.Path & "\\ModelOutputFiles\06_ModelRecResults.txt" For
Output As #6
```

```
Open App.Path & "\\ModelOutputFiles\07_TimeStepYldTempFile.txt" For
Output As #7
```

```
Print #3, "i", "j", "k", "HRU", "SUB", "LULC", "Month",
"Iteration", "PCrop($/ton)", "ActYld(t/ha)", "TimeStepYLD",
"TargetYld", "PotCalcYld", "MaxSwatYld", "Ky", "ActET(mm)",
"TargetET(mm)", "MaxAET", "PotET(mm)", "CComb($/yr)", "AnnDep($/yr)",
"MonDep($/mo)", "Area(km^2)", "CWater($/ha)", "TotExpenses",
"TotRevenue", "CalcNetB"
```

```
Write #6, "i", "j", "k", "HRU", "SUB", "LULC", "Month",
"OptIteration", "IrrSys", "OptIrrDepth", "OptIrrVol", "OptActIrrYld",
"OptActIrrET", "MaxNetBenefitWI"
```

```
Print #7, "HRU", "Month", "ActYTDYield", "TimeStepYield",
"TargetYld", "MaxYld", "PotentialCalcYld"
```

```
'Opens Monthly Output Tables
```

```
Open App.Path & "\\ModelOutputFiles\15_MoHRUSumData.txt" For Output
As #15
```

```
Open App.Path & "\\ModelOutputFiles\16_MoSubSumData.txt" For Output
As #16
```

```
Open App.Path & "\\ModelOutputFiles\17_MoWatSumData.txt" For Output
As #17
```

```
Print #15, "Irr_Sys", "Sub", "HRU", "Month", "Avg.Mo.IrrD",
"Avg.Mo.IrrV", "Avg.Mo.NB.WOI", "Avg.Mo.NB.WI"
```

```
Print #16, "Irr_Sys", "Sub", "Month", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.NB.WI", "Avg.Mo.NB.WOI"
```

```
Print #17, "Irr_Sys", "Month", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.NB.WOI", "Avg.Mo.NB.WI"
```

```
End Sub
```

```
'STEP 3: 4th Level Support Procedures
```

```
Public Sub OpenNBPrintFiles(iIrrCtr As Integer)
```

```
Dim sOptIrrSchedFileName As String
```

```
Dim sRecIrrSysFileName As String
```

```
sOptIrrSchedFileName = App.Path &
"\\ModelOutputFiles\22_OptimalIrrSched_" & sIrrSys(iIrrCtr) & ".txt"
sRecIrrSysFileName = App.Path & "\\ModelOutputFiles\23_RecIrrSys_" &
sIrrSys(iIrrCtr) & ".txt"
```

```
Open sOptIrrSchedFileName For Output As #22
```

```
Open sRecIrrSysFileName For Output As #23
```

```
Print #22,
Print #22, "For Irrigation System ID: ", sIrrSys(iIrrCtr)
Print #22, "Sub", "HRU", "Month", "IrrSys", "OptIrrDepth",
"OptIrrVol", "Ratio TET/MET", "TargetET", "TargetYld"
Print #23,
Print #23, "For Irrigation System ID: ", sIrrSys(iIrrCtr)
Print #23, "Sub", "HRU", "Month", "IrrSys", "NB: W/O Irrig", "NB: W
Irrig"
```

```

'Opens General output tables
Open App.Path & "\\ModelOutputFiles\09_HRUSumMoData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #9
Open App.Path & "\\ModelOutputFiles\10_SubSumMoData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #10
Open App.Path & "\\ModelOutputFiles\11_WatSumMoData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #11
Open App.Path & "\\ModelOutputFiles\12_HRUSumYrData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #12
Open App.Path & "\\ModelOutputFiles\13_SubSumYrData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #13
Open App.Path & "\\ModelOutputFiles\14_WatSumYrData_" &
sIrrSys(iIrrCtr) & ".txt" For Output As #14

Print #9, "Irr_Sys", "Sub", "HRU", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.NB.WOI", "Avg.Mo.NB.WI"
Print #10, "Irr_Sys", "Sub", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.NB.WOI", "Avg.Mo.NB.WI"
Print #11, "Irr_Sys", "Avg.Mo.IrrD", "Avg.Mo.IrrV",
"Avg.Mo.NB.WOI", "Avg.Mo.NB.WI"
Print #12, "Irr_Sys", "Sub", "HRU", "Avg.Yr.IrrD", "Avg.Yr.IrrV",
"Avg.Yr.NB.WOI", "Avg.Yr.NB.WI"
Print #13, "Irr_Sys", "Sub", "Avg.Yr.IrrD", "Avg.Yr.IrrV",
"Avg.Yr.NB.WOI", "Avg.Yr.NB.WI"
Print #14, "Irr_Sys", "Avg.Yr.IrrD", "Avg.Yr.IrrV", "Avg.Yr.NB.WOI",
"Avg.Yr.NB.WI"
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub CloseNBPrintFiles()
Close #22
Close #23
Close #9
Close #10
Close #11
Close #12
Close #13
Close #14
End Sub

'STEP 3: 4th Level Support Procedures
Public Function SetEconCtr(lSwatCtr As Long)
Dim k As Integer 'For Loop counter

'this runs through the econ data loaded and selects the crop type
associatd with HRU
For k = 0 To 12
If sEconIdCrop(k) = sLulc(lSwatCtr) Then
SetEconCtr = k
Exit For
Else: End If
Next k
End Function

'STEP 3: 4th Level Support Procedures
Public Function SetMaxETDif()

```



```

Dim i As Long 'counter
Dim iMaxETDif As Integer

iMaxETDif = 0
For i = 0 To iSwatArraySize
    If iETDif(i) > iMaxETDif Then
        iMaxETDif = iETDif(i)
    Else: End If
Next i

SetMaxETDif = iMaxETDif
End Function

'STEP 3: 4th Level Support Procedures
Public Sub RunNBCalculations(iIrrCtr As Integer)
    Dim lSwatCtr As Long 'counter for Swat array variables
    Dim iEconCtr As Integer 'counter for Econ array variables
    Dim iItCtr As Integer 'counter for repetative iterations
    Dim i As Long 'counter for number of SWAT data records
    Dim j As Long 'counter for the irrigation system being calculated.
    Dim k As Integer 'counter for the number of economic data records
    'The following are Temp arrays that are used during the iteration
    process to hold temporary values during NB calculations
    Dim sNetBenefitWOIHolder As Single
    Dim sTargetETTemp() As Single
    Dim sIrrDepthTemp() As Single
    Dim sIrrVolTemp() As Single 'This is being calculated in units of
    m^3/ha
    Dim sNetBenefitTemp() As Single
    Dim sNetBenefitWOITemp() As Single
    Dim sYldDivisorTemp() As Single ' this value is the value the
    Yield is divided by in the equation above
    Dim sProdCostTemp() As Single
    Dim sRevenueTemp() As Single
    Dim sWaterCostTemp() As Single
    Dim sRatioTetPetTemp() As Single
    Dim sRatioTetMetTemp() As Single
    Dim sTargetYldTemp() As Single
    Dim iMaxItCtr As Integer 'is set equal to the max size of
    difference between Potential ET and Actual ET
    Dim iOptIt As Integer 'the iteration at which the greatest net
    benefit is achieved.
    Dim sExpensesTem As Single 'Holds the value of the Expenses in
    the determination of NetBenefit
    Dim sRevenueTem As Single 'Holds the value of the Revenue used in
    teh determination of NetBenefit

    iMaxItCtr = SetMaxETDif

    'the following ReDims the Temp arrays to the size of the Agrr-Swat
    data file.
    ReDim sTargetETTemp(iMaxItCtr) As Single
    ReDim sIrrDepthTemp(iMaxItCtr) As Single
    ReDim sIrrVolTemp(iMaxItCtr) As Single
    ReDim sNetBenefitTemp(iMaxItCtr) As Single
    ReDim sNetBenefitWOITemp(iMaxItCtr) As Single

```

```

ReDim sYldDivisorTemp(iMaxItCtr) As Single
ReDim sProdCostTemp(iMaxItCtr) As Single
ReDim sRevenueTemp(iMaxItCtr) As Single
ReDim sWaterCostTemp(iMaxItCtr) As Single
ReDim sRatioTetPetTemp(iMaxItCtr) As Single
ReDim sRatioTetMetTemp(iMaxItCtr) As Single
ReDim sTargetYldTemp(iMaxItCtr) As Single

j = iIrrCtr

For i = 0 To iSwatArraySize
  lSwatCtr = i
  iEconCtr = SetEconCtr(lSwatCtr)
  iItCtr = 0
  sIrrDepthTemp(0) = 0

  'The following section calculates the net benefit without
  irrigation. (this section only uses data from the SWAT simulation
  without irrigation.
  'Call SetNBParamWOI(i, j, k, lSwatCtr, iItCtr, iEconCtr, iIrrCtr)
    ' The following three equations calculate NetBenefit when
    there is no irrigation applied (sIrrDepth = 0) and there are no
    equipment costs.
    ' Note that in this case the iItCtr = 0, indicating no
    irrigation is applied.
    sTargetETTemp(iItCtr) = sAEt(lSwatCtr) +
sIrrDepthTemp(iItCtr)
    sIrrVolTemp(iItCtr) = (sIrrDepthTemp(iItCtr) * 10) /
(sIrrEff(iIrrCtr))
    sYldDivisorTemp(iItCtr) = (1 - sEconKy(iEconCtr) * (1 -
(sAEt(lSwatCtr) / sTargetETTemp(iItCtr))))
    sProdCostTemp(iItCtr) = ((sEconCComb(iEconCtr) / 12) *
sArea(lSwatCtr) * 100)
    sWaterCostTemp(iItCtr) = sIrrVolTemp(iItCtr) *
sEconCWater(iEconCtr)
    sTargetYldTemp(iItCtr) = sTimeStepYldMax(lSwatCtr) * (1 -
sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr))))

    'The following two equations determine the yield and
    maximum yield using the original yield equation.
    sTimeStepCalcPotentialYld(lSwatCtr) =
sTimeStepYld(lSwatCtr) / (1 - sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr)
/ sAEtMax(lSwatCtr))))
    sTimeStepCalcActYld(lSwatCtr) = sTimeStepYldMax(lSwatCtr) *
(1 - sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr) / sAEtMax(lSwatCtr))))

    'The following two equations determine the revised yield
    and maximum yield equations.
    sTimeStepCalcPotentialYld2(lSwatCtr) =
sTimeStepYld(lSwatCtr) / (1 - sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr)
/ sAEtMax(lSwatCtr))))
    sTimeStepCalcActYld2(lSwatCtr) = sTimeStepYldMax(lSwatCtr)
* (1 - sEconKy(iEconCtr) * (1 - (sAEt(lSwatCtr) / sAEtMax(lSwatCtr))))

    'sTargetETTemp(iItCtr) = sAEt(lSwatCtr)

```

```

'sTargetYldTemp(iItCtr) = sTimeStepYldMax(lSwatCtr) * (1 -
sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr))))

sRevenueTem = sEconPCrop(iEconCtr) * sTargetYldTemp(iItCtr)
sExpensesTem = (sEconCComb(iEconCtr) / 12)
sNetBenefitTemp(iItCtr) = sRevenueTem - sExpensesTem

sMaxNetBenefitWOI(lSwatCtr) = sNetBenefitTemp(iItCtr)
sNetBenefitWOI(lSwatCtr) = sNetBenefitTemp(iItCtr)
sNetBenefitWOIHolder = sNetBenefitTemp(iItCtr)

' This section calculates the NetBenefit with Irrigation It uses
some data from the SWAT simulation with 100% irrigation.
' Call SetNBParamWI(i, j, k, lSwatCtr, iItCtr, iEconCtr, iIrrCtr)
iItCtr = iItCtr + 1
sIrrDepthTemp(iItCtr) = sIrrDepthTemp(iItCtr - 1) + 1

' The following three equations calculate NetBenefit when
there is irrigation applied (sIrrDepth = 0) and there are no equipment
costs.

sTargetETTemp(iItCtr) = sAEt(lSwatCtr) +
sIrrDepthTemp(iItCtr)
sIrrVolTemp(iItCtr) = (sIrrDepthTemp(iItCtr) * 10) /
(sIrrEff(iIrrCtr))
sYldDivisorTemp(iItCtr) = 1 - (sEconKy(iEconCtr) * (1 -
(sAEt(lSwatCtr) / sTargetETTemp(iItCtr))))
sProdCostTemp(iItCtr) = ((sEconCComb(iEconCtr) / 12) *
sArea(lSwatCtr) * 100) + sMonDep(iIrrCtr) + sMonMain_ha(iIrrCtr)
sWaterCostTemp(iItCtr) = sIrrVolTemp(iItCtr) *
sEconCWater(iEconCtr)
sTargetYldTemp(iItCtr) = sTimeStepYldMax(lSwatCtr) * (1 -
sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr))))
sRevenueTemp(iItCtr) = sEconPCrop(iEconCtr) *
sTargetYldTemp(iItCtr)

sRevenueTem = sEconPCrop(iEconCtr) * sTargetYldTemp(iItCtr)
sExpensesTem = (sEconCComb(iEconCtr) / 12) +
sMonDep(iIrrCtr) + sMonMain_ha(iIrrCtr) + (sIrrVolTemp(iItCtr) *
sEconCWater(iEconCtr))
sNetBenefitTemp(iItCtr) = sRevenueTem - sExpensesTem

Print #3, i, j, k, iHru(lSwatCtr), iSub(lSwatCtr),
sLulc(lSwatCtr), iMon(lSwatCtr), iItCtr, sEconPCrop(iEconCtr),
sYLD(lSwatCtr), sTimeStepYld(lSwatCtr), sTargetYldTemp(iItCtr),
"sTimeStepPotentialYld(lSwatCtr),"; sYldMax(lSwatCtr),
sEconKy(iEconCtr), sAEt(lSwatCtr), sTargetETTemp(iItCtr),
sAEtMax(lSwatCtr), sPet(lSwatCtr), sEconCComb(iEconCtr),
sAnnDep(iIrrCtr), sMonDep(iIrrCtr), sArea(lSwatCtr),
sWaterCostTemp(iItCtr), sExpensesTem, sRevenueTem,
sNetBenefitTemp(iItCtr)

Print #4, i, j, k, iHru(lSwatCtr), iSub(lSwatCtr),
sLulc(lSwatCtr), iMon(lSwatCtr), iItCtr, sYldDivisorTemp(iItCtr),
sAEt(lSwatCtr), sIrrDepthTemp(iItCtr), sTargetETTemp(iItCtr),
sAEtMax(lSwatCtr), sPet(lSwatCtr), sIrrVolTemp(iItCtr),
sNetBenefitTemp(iItCtr)
Do

```

```

        'Call SetNBParamWI(i, j, k, lSwatCtr, iItCtr, iEconCtr,
iIrrCtr)
        iItCtr = iItCtr + 1

        If iItCtr >= sIrrMax(lSwatCtr) Then
        Exit Do
        Else: End If

                sIrrDepthTemp(iItCtr) = sIrrDepthTemp(iItCtr - 1) + 1

                ' The following three equations calculate NetBenefit when
there is irrigation applied (sIrrDepth = 0) and there are no equipment
costs.
                sTargetETTemp(iItCtr) = sAEt(lSwatCtr) +
sIrrDepthTemp(iItCtr)

                'section is just added.... CHECK March 26,2006

                If sTargetETTemp(iItCtr) >= sAEtMax(lSwatCtr) Then
                Exit Do
                Else: End If

                        sIrrVolTemp(iItCtr) = (sIrrDepthTemp(iItCtr) * 10) /
(sIrrEff(iIrrCtr))
                        sYldDivisorTemp(iItCtr) = 1 - (sEconKy(iEconCtr) * (1 -
(sAEt(lSwatCtr) / sTargetETTemp(iItCtr))))
                        sProdCostTemp(iItCtr) = ((sEconCComb(iEconCtr) / 12) *
sArea(lSwatCtr) * 100) + sMonDep(iIrrCtr) + sMonMain_ha(iIrrCtr)
                        sWaterCostTemp(iItCtr) = sIrrVolTemp(iItCtr) *
sEconCWater(iEconCtr)
                        sTargetYldTemp(iItCtr) = sTimeStepYldMax(lSwatCtr) * (1 -
sEconKy(iEconCtr) * (1 - (sTargetETTemp(iItCtr) / sAEtMax(lSwatCtr))))
                        sRevenueTemp(iItCtr) = sEconPCrop(iEconCtr) *
sTargetYldTemp(iItCtr)

                        sRevenueTem = sEconPCrop(iEconCtr) * sTargetYldTemp(iItCtr)
                        sExpensesTem = (sEconCComb(iEconCtr) / 12) +
sMonDep(iIrrCtr) + sMonMain_ha(iIrrCtr) + (sIrrVolTemp(iItCtr) *
sEconCWater(iEconCtr))
                        sNetBenefitTemp(iItCtr) = sRevenueTem - sExpensesTem

                If (sNetBenefitTemp(iItCtr - 1) > sNetBenefitTemp(iItCtr)) Then
                Exit Do
                Else: End If

                Loop While sNetBenefitTemp(iItCtr - 1) <
sNetBenefitTemp(iItCtr)

                'This if-then statement determines if irrigation is beneficial.
If sNetBenefitTemp(iItCtr - 1) > sNetBenefitTemp(0) Then
                iOptIt = iItCtr - 1
        Else: iOptIt = 0
        End If

        sOptIrrDepth(lSwatCtr) = sIrrDepthTemp(iOptIt)

```

```

sOptIrrVol(lSwatCtr) = sIrrVolTemp(iOptIt)
sRatioTetPetTemp(iOptIt) = sTargetETTemp(iOptIt) / sPet(lSwatCtr)
sRatioTetMetTemp(iOptIt) = sTargetETTemp(iOptIt) /
sAEtMax(lSwatCtr)

sOptActIrrYld(lSwatCtr) = sTargetYldTemp(iOptIt)
sOptActIrrET(lSwatCtr) = sTargetETTemp(iOptIt)

'Note that if iOptIt is =0 then this means that irrigation is not
Recommended. However, do determine the NetBenefit of irrigation we must
still
'include the cost of the irrigation system. Therefore, if iOptIt
is zero we must report the NetBenefit at Iteration = 1 as the
MaxNetBenefit with Irrigation
'this iteration will include the cost of applying lmm of water to
the entire area over the month, even if irrigation is not Recommended.
'We will consider this to be the cost of operating the system.
If iOptIt = 0 Then
iOptIt = iOptIt + 1
sOptIrrDepth(lSwatCtr) = 0
sIrrDepthTemp(iOptIt) = 0
Else: End If
sMaxNetBenefitWI(lSwatCtr) = sNetBenefitTemp(iOptIt)

sTargetET(i) = sTargetETTemp(iOptIt)
sIrrDepth(i) = sIrrDepthTemp(iOptIt)
sIrrVol(i) = sIrrVolTemp(iOptIt)
sNetBenefit(i) = sNetBenefitTemp(iOptIt)
sYldDivisor(i) = sYldDivisorTemp(iOptIt)
sProdCost(i) = sProdCostTemp(iOptIt)
sRevenue(i) = sRevenueTemp(iOptIt)
sWaterCost(i) = sWaterCostTemp(iOptIt)
sTargetYld(i) = sTargetYldTemp(iOptIt)
sRatioTetPet(i) = sRatioTetPetTemp(iOptIt)
sRatioTetMet(i) = sRatioTetMetTemp(iOptIt)

Write #6, i, j, k, iHru(lSwatCtr), iSub(lSwatCtr), sLulc(lSwatCtr),
iMon(lSwatCtr), iOptIt, sIrrSys(iIrrCtr), sOptIrrDepth(lSwatCtr),
sOptIrrVol(lSwatCtr), sOptActIrrYld(lSwatCtr), sOptActIrrET(lSwatCtr),
sMaxNetBenefitWI(lSwatCtr)
Print #7, iHru(lSwatCtr), iMon(lSwatCtr), sYLD(lSwatCtr),
sTimeStepYld(lSwatCtr), sTargetYld(lSwatCtr), sYldMax(lSwatCtr),
sTimeStepCalcPotentialYld(lSwatCtr)

'The following code is intended to break the program if the NBdif
gets to be too high.

sMaxNetBenefitDif(lSwatCtr) = sMaxNetBenefitWI(lSwatCtr) -
sMaxNetBenefitWOI(lSwatCtr)

Next i

Call GenerateOutputTables(iIrrCtr) 'Prints and Averages Optimal
Irrigation Depth/Volume and Net Benefit Values.
Call GenerateSummaryTables(iIrrCtr)
Call GenerateMoSummaryTables(iIrrCtr)
End Sub

```

```

'STEP 3: 4th Level Support Procedures
Public Sub SetNBParamWOI(i As Long, j As Long, k As Integer, lSwatCtr
As Long, iItCtr As Integer, iEconCtr As Integer, iIrrCtr As Integer)

End Sub

'STEP 3: 4th Level Support Procedures
Public Sub SetNBParamWI(i As Long, j As Long, k As Integer, lSwatCtr As
Long, iItCtr As Integer, iEconCtr As Integer, iIrrCtr As Integer)

End Sub

'STEP 3: 4th Level Support Procedures
Public Sub GenerateOutputTables(iIrrCtr)
    Dim i As Long 'general counter

    For i = 0 To iSwatArraySize
        Print #22, iSub(i), iHru(i), iMon(i), sIrrSys(iIrrCtr),
sOptIrrDepth(i), sOptIrrVol(i), sRatioTetMet(i), sTargetET(i),
sTargetYld(i)
        Print #23, iSub(i), iHru(i), iMon(i), sIrrSys(iIrrCtr),
sMaxNetBenefitWOI(i), sMaxNetBenefitWI(i)
    Next i
End Sub

'STEP 3: 4th Level Support Procedures
Public Sub GenerateSummaryTables(iIrrCtr As Integer)
    Dim i As Long 'integer counter for all Swat records
    Dim j As Integer 'integer counter for all Hru's in Swat data
    Dim k As Integer 'integer counter for all Sub's in Swat data
    Dim m As Integer 'integer counter for setting NB calculations
    Dim lMonths As Long 'month counter
    Dim sYears As Single 'used to determine the number of months.
    Dim sIrrDTotal As Single 'value holder for averaging later.
    Dim sIrrVTTotal As Single 'value holder for averageing
    Dim sIrrNBWOITotal As Single 'value holder for averaging
    Dim sIrrNBWITotal As Single 'value holder for averaging
    Dim iHruMarker As Long 'value used to mark the Hru Number under
analysis
    Dim iSubMarker As Long 'value used to mark the Sub Number under
analysis.
    Dim iHruCtr As Long 'value used to mark the Hru Number under
analysis
    Dim iSubCtr As Long 'value used to mark the Sub Number under
analysis.
    Dim iSubHruCtr As Integer ' value used to count the number of Hru's
within a Subbassin.

    'Finds the Number of Hru's and ReDims the Array
    Call ReDimHruSummary

    'Finds the Number of Sub's number and ReDims the Array
    Call ReDimSubSummary

```

'Calculates the average monthly irrigation application depth for each HRU for all years of the Swat simulation.

```
iHruCtr = iHru(0)

For j = 0 To iNumHru
sIrrDTotal = 0
sIrrVTTotal = 0
sIrrNBWITotal = 0
sIrrNBWOITotal = 0

lMonths = 0
For i = 0 To iSwatArraySize
  If iHru(i) = iHruCtr Then
    iHruMarker = i
    sIrrDTotal = sIrrDTotal + sIrrDepth(i)
    sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
    sIrrNBWITotal = sIrrNBWITotal + sNetBenefit(i)
    sIrrNBWOITotal = sIrrNBWOITotal + sNetBenefitWOI(i)
    lMonths = lMonths + 1
  Else: End If
Next i
iHruCtr = iHru(j)

If lMonths > 0 Then
  iHruHruSum(j) = iHru(iHruMarker)
  iSubHruSum(j) = iSub(iHruMarker)

  sYears = lMonths / 12
  sAvgIrrDHruMo(j) = sIrrDTotal / lMonths
  sAvgIrrDHruYr(j) = sIrrDTotal / sYears
  sAvgIrrVHruMo(j) = sIrrVTTotal / lMonths
  sAvgIrrVHruYr(j) = sIrrVTTotal / sYears
  sAvgIrrNBWIHruMo(j) = sIrrNBWITotal / lMonths
  sAvgIrrNBWIHruYr(j) = sIrrNBWITotal / sYears
  sAvgIrrNBWOIHruMo(j) = sIrrNBWOITotal / lMonths
  sAvgIrrNBWOIHruYr(j) = sIrrNBWOITotal / sYears
Else: End If

Next j
```

'Calculates the average monthly irrigation application depth for each SUB for all years of the Swat simulation.

```
iSubCtr = 1

For k = 1 To iSubHigh
sIrrDTotal = 0
sIrrVTTotal = 0
sIrrNBWITotal = 0
sIrrNBWOITotal = 0
iSubHruCtr = 0
For i = 0 To iSwatArraySize
  If iSub(i) = iSubCtr Then
    iSubMarker = i
    sIrrDTotal = sIrrDTotal + sIrrDepth(i)
    sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
    sIrrNBWITotal = sIrrNBWITotal + sNetBenefit(i)
```

```

        sIrrNBWOITotal = sIrrNBWOITotal + sNetBenefitWOI(i)
        iSubHruCtr = iSubHruCtr + 1
    Else: End If
Next i
iSubCtr = iSubCtr + 1
iSubSubSum(k - 1) = iSub(iSubMarker)
iSubHruCtr = iSubHruCtr / lMonths

sAvgIrrDSubMo(k - 1) = (sIrrDTTotal / lMonths) / iSubHruCtr
sAvgIrrDSubYr(k - 1) = (sIrrDTTotal / sYears) / iSubHruCtr
sAvgIrrVSubMo(k - 1) = sIrrVTTotal / lMonths
sAvgIrrVSubYr(k - 1) = sIrrVTTotal / sYears
sAvgIrrNBWISubMo(k - 1) = sIrrNBWITotal / lMonths
sAvgIrrNBWISubYr(k - 1) = sIrrNBWITotal / sYears
sAvgIrrNBWOISubMo(k - 1) = sIrrNBWOITotal / lMonths
sAvgIrrNBWOISubYr(k - 1) = sIrrNBWOITotal / sYears
Next k

```

'Calculates the average monthly irrigation application depth for the entire watershed for all years of the Swat simulation.

```

sIrrDTTotal = 0
sIrrVTTotal = 0
sIrrNBWITotal = 0
sIrrNBWOITotal = 0
lMonths = 0

For i = 0 To iSwatArraySize
    sIrrDTTotal = sIrrDTTotal + sIrrDepth(i)
    sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
    sIrrNBWITotal = sIrrNBWITotal + sNetBenefit(i)
    sIrrNBWOITotal = sIrrNBWOITotal + sNetBenefitWOI(i)
    lMonths = lMonths + 1
Next i

sYears = lMonths / (13 * iNumHru)

sAvgIrrDWatMo = (sIrrDTTotal / lMonths) / (iNumHru + 1)
sAvgIrrDWatYr = (sIrrDTTotal / sYears) / (iNumHru + 1)
sAvgIrrVWatMo = sIrrVTTotal / lMonths
sAvgIrrVWatYr = sIrrVTTotal / sYears
sAvgIrrNBWIWatMo = sIrrNBWITotal / lMonths
sAvgIrrNBWIWatYr = sIrrNBWITotal / sYears
sAvgIrrNBWOIWatMo = sIrrNBWOITotal / lMonths
sAvgIrrNBWOIWatYr = sIrrNBWOITotal / sYears

'The following lines write to text files
j = 0
For j = 1 To (iNumHru)
    Print #9, sIrrSys(iIrrCtr), iSubHruSum(j), iHruHruSum(j),
sAvgIrrDHruMo(j), sAvgIrrVHruMo(j), sAvgIrrNBWOIHruMo(j),
sAvgIrrNBWIHruMo(j)
    Print #12, sIrrSys(iIrrCtr), iSubHruSum(j), iHruHruSum(j),
sAvgIrrDHruYr(j), sAvgIrrVHruYr(j), sAvgIrrNBWOIHruYr(j),
sAvgIrrNBWIHruYr(j)
Next j

```



```

    k = 0
    For k = 0 To (iSubHigh - 1)
        Print #10, sIrrSys(iIrrCtr), iSubSubSum(k), sAvgIrrDSubMo(k),
sAvgIrrVSubMo(k), sAvgIrrNBWOISubMo(k), sAvgIrrNBWISubMo(k)
        Print #13, sIrrSys(iIrrCtr), iSubSubSum(k), sAvgIrrDSubYr(k),
sAvgIrrVSubYr(k), sAvgIrrNBWOISubYr(k), sAvgIrrNBWISubYr(k)
    Next k

    Print #11, sIrrSys(iIrrCtr), sAvgIrrDWatMo, sAvgIrrVWatMo,
sAvgIrrNBWOIWatMo, sAvgIrrNBWIWatMo
    Print #14, sIrrSys(iIrrCtr), sAvgIrrDWatYr, sAvgIrrVWatYr,
sAvgIrrNBWOIWatYr, sAvgIrrNBWIWatYr

    'The following lines store needed values used in the determination
of the best recommended irrigation system.
    Call ReDimNBRecVariables

    For j = 1 To iNumHru
        If iIrrCtr = 0 Then
            sCPivotNBWOIYr(j) = sAvgIrrNBWOIHruYr(j)
            sCPivotNBWIYr(j) = sAvgIrrNBWIHruYr(j)
            sCPivotNBDifYr(j) = sCPivotNBWIYr(j) - sCPivotNBWOIYr(j)
            sCPivotIrrVolYr(j) = sAvgIrrVHruYr(j)

            Write #21, iIrrCtr, iHru(j), sIrrSys(iIrrCtr),
sCPivotNBWOIYr(j), sCPivotNBWIYr(j), sCPivotNBDifYr(j),
sCPivotIrrVolYr(j)

        Else: End If

        If iIrrCtr = 1 Then
            sTGunNBWOIYr(j) = sAvgIrrNBWOIHruYr(j)
            sTGunNBWIYr(j) = sAvgIrrNBWIHruYr(j)
            sTGunNBDifYr(j) = sTGunNBWIYr(j) - sTGunNBWOIYr(j)
            sTGunIrrVolYr(j) = sAvgIrrVHruYr(j)

            Write #21, iIrrCtr, iHru(j), sIrrSys(iIrrCtr),
sTGunNBWOIYr(j), sTGunNBWIYr(j), sTGunNBDifYr(j), sTGunIrrVolYr(j)

        Else: End If

        If iIrrCtr = 2 Then
            sDripNBWOIYr(j) = sAvgIrrNBWOIHruYr(j)
            sDripNBWIYr(j) = sAvgIrrNBWIHruYr(j)
            sDripNBDifYr(j) = sDripNBWIYr(j) - sDripNBWOIYr(j)
            sDripIrrVolYr(j) = sAvgIrrVHruYr(j)

            Write #21, iIrrCtr, iHru(j), sIrrSys(iIrrCtr),
sDripNBWOIYr(j), sDripNBWIYr(j), sDripNBDifYr(j), sDripIrrVolYr(j)

        Else: End If
    Next j
End Sub

'STEP 3: 4th Level Support Procedures

```

```

Public Sub GenerateMoSummaryTables(iIrrCtr As Integer) 'This sub
section generates the Output files 15, 16 and 17
    Dim i As Long 'integer counter for all Swat records
    Dim j As Integer 'integer counter for all Hru's in Swat data
    Dim k As Integer 'integer counter for all Sub's in Swat data
    Dim m As Integer 'indicates the month being analysed.
    Dim iMonths As Integer 'month counter
    Dim sYears As Single 'used to determine the number of months.
    Dim sIrrDTotal As Single 'value holder for averaging later.
    Dim sIrrVTTotal As Single 'value holder for averaging
    Dim sNBWITotal As Single ' value holder for averaging Net Benefit
With Irrigation
    Dim sNBWOITotal As Single 'value holder for averaging Net Benefit
Without Irrigation
    Dim iHruMarker As Long 'value used to mark the Hru Number under
analysis
    Dim iSubMarker As Long 'value used to mark the Sub Number under
analysis.
    Dim iHruCtr As Integer 'value used to mark the Hru Number under
analysis
    Dim iSubCtr As Integer 'value used to mark the Sub Number under
analysis.
    Dim iArrayCtr As Integer 'used to track the array subscript

    'Calculates the average monthly irrigation application depth for
each HRU for all years of the Swat simulation.
    iHruCtr = iHru(0)
    iArrayCtr = 0

    For j = 1 To iNumHru
        For m = 1 To 12
            sIrrDTotal = 0
            sIrrVTTotal = 0
            sNBWITotal = 0
            sNBWOITotal = 0
            iMonths = 0
            For i = 0 To iSwatArraySize
                If (iHru(i) = iHruCtr) And (iMon(i) = m) Then
                    iHruMarker = i
                    sIrrDTotal = sIrrDTotal + sIrrDepth(i)
                    sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
                    sNBWITotal = sNBWITotal + sNetBenefit(i)
                    sNBWOITotal = sNBWOITotal + sNetBenefitWOI(i)
                    iMonths = iMonths + 1
                Else: End If
            Next i

            If iMonths > 0 Then
                iMoHruHruSum(iArrayCtr) = iHru(iHruMarker)
                iMoSubHruSum(iArrayCtr) = iSub(iHruMarker)
                iMoMonHruSum(iArrayCtr) = m
                sMoAvgIrrDHruMo(iArrayCtr) = sIrrDTotal / iMonths
                sMoAvgIrrVHruMo(iArrayCtr) = sIrrVTTotal / iMonths
                sMoAvgNBWIHruMo(iArrayCtr) = sNBWITotal / iMonths
                sMoAvgNBWOIHruMo(iArrayCtr) = sNBWOITotal / iMonths

                iArrayCtr = iArrayCtr + 1
            End If
        Next m
    Next j
End Sub

```

```

        Else: End If
    Next m
    iHruCtr = iHru(j)
Next j

iMoNumHru = iArrayCtr 'Holds the size of the Array

'Calculates the average monthly irrigation application depth for
each SUB for all years of the Swat simulation.
iArrayCtr = 0
iSubCtr = 1

For k = 1 To iSubHigh
    For m = 1 To 12
        sIrrDTotal = 0
        sIrrVTTotal = 0
        sNBWITotal = 0
        sNBWOITotal = 0
        iMonths = 0
        For i = 0 To iSwatArraySize
            If (iSub(i) = iSubCtr) And (iMon(i) = m) Then
                iSubMarker = i
                sIrrDTotal = sIrrDTotal + sIrrDepth(i)
                sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
                sNBWITotal = sNBWITotal + sNetBenefit(i)
                sNBWOITotal = sNBWOITotal + sNetBenefitWOI(i)
                iMonths = iMonths + 1
            Else: End If
        Next i

        If iMonths > 0 Then
            iMoSubSubSum(iArrayCtr) = iSub(iSubMarker)
            iMoMonSubSum(iArrayCtr) = m
            sMoAvgIrrDSubMo(iArrayCtr) = sIrrDTotal / iMonths
            sMoAvgIrrVSubMo(iArrayCtr) = sIrrVTTotal / iMonths
            sMoAvgNBWISubMo(iArrayCtr) = sNBWITotal / iMonths
            sMoAvgNBWOISubMo(iArrayCtr) = sNBWOITotal / iMonths
            iArrayCtr = iArrayCtr + 1
        Else: End If
    Next m
    iSubCtr = iSubCtr + 1
Next k

iMoNumSub = iArrayCtr 'holds the size of the array

'Calculates the average monthly irrigation application depth for
the entire watershed for all years of the Swat simulation.
iArrayCtr = 0

For m = 1 To 12
    sIrrDTotal = 0
    sIrrVTTotal = 0
    sNBWITotal = 0
    sNBWOITotal = 0
    iMonths = 0
    For i = 0 To iSwatArraySize
        If iMon(i) = m Then

```

```

        sIrrDTotal = sIrrDTotal + sIrrDepth(i)
        sIrrVTTotal = sIrrVTTotal + sIrrVol(i)
        sNBWITotal = sNBWITotal + sNetBenefit(i)
        sNBWOITotal = sNBWOITotal + sNetBenefitWOI(i)
        iMonths = iMonths + 1
    Else: End If
Next i
If iMonths <> 0 Then
    iMoMonWatMo(iArrayCtr) = m
    sMoAvgIrrDWatMo(iArrayCtr) = sIrrDTotal / iMonths
    sMoAvgIrrVWatMo(iArrayCtr) = sIrrVTTotal / iMonths
    sMoAvgNBWIWatMo(iArrayCtr) = sNBWITotal / iMonths
    sMoAvgNBWOIWatMo(iArrayCtr) = sNBWOITotal / iMonths
Else: End If
iArrayCtr = iArrayCtr + 1
Next m

For i = 0 To (iMoNumHru - 1)
    Print #15, sIrrSys(iIrrCtr), iMoSubHruSum(i), iMoHruHruSum(i),
iMoMonHruSum(i), sMoAvgIrrDHruMo(i), sMoAvgIrrVHruMo(i),
sMoAvgNBWIHruMo(i), sMoAvgNBWOIHruMo(i)
Next i

For j = 0 To (iMoNumSub - 1)
    Print #16, sIrrSys(iIrrCtr), iMoSubSubSum(j), iMoMonSubSum(j),
sMoAvgIrrDSubMo(j), sMoAvgIrrVSubMo(j), sMoAvgNBWISubMo(j),
sMoAvgNBWOISubMo(j)
Next j

For k = 0 To 11
    Print #17, sIrrSys(iIrrCtr), iMoMonWatMo(k),
sMoAvgIrrDWatMo(k), sMoAvgIrrVWatMo(k), sMoAvgNBWIWatMo(k),
sMoAvgNBWOIWatMo(k)
Next k
End Sub

'STEP 4: Primary Call Procedures for DDS
'Procedures required to make Irrigation Recommendations

Private Sub cmdIrrVol_Click()
    Load frmResultsOptVol
    frmResultsOptVol.Show
End Sub

Private Sub cmdRecommendations_Click()
    Load frmResultsSysRec
    frmResultsSysRec.Show
End Sub

'STEP 4: 2nd Level Call Procedures for DDS
'Optimal Irrigation Calculations
Public Sub CalcOptimalIrrVol()
    Dim i As Integer 'general counter for Hru's
    Dim j As Integer 'general counter for irrigation systems
    Dim sTotIrrVolTemp As Single ' value holder of Irrigation volume
applied.

```

```

    Dim sTotIrrVolWatYr As Single ' total applied irrigation water for
the entire watershed.
    Dim sTotIrrVolCPivotYr As Single 'm^3 for all Agrr fields within
the watershed
    Dim sTotIrrVolTGunYr As Single 'm^3 for all AGRR fields within
the watershed
    Dim sTotIrrVolDripYr As Single 'm^3 for all AGRR fields within
the watershed
    Dim sAvgIrrVolWatYr As Single 'average water consumption for
the year m^3/ha
    Dim sAvgIrrVolCPivotYr As Single
    Dim sAvgIrrVolTGunYr As Single
    Dim sAvgIrrVolDripYr As Single

For i = 1 To iNumHru
sTotIrrVolTemp = 0
If iRecIrrSysInt(i) = 0 Then
    sTotIrrVolTemp = sTotIrrVolTemp + sCPivotIrrVolYr(i)
Else:
    If iRecIrrSysInt(i) = 1 Then
        sTotIrrVolTemp = sTotIrrVolTemp + sTGunIrrVolYr(i + iNumHru)
    Else:
        If iRecIrrSysInt(i) = 2 Then
            sTotIrrVolTemp = sTotIrrVolTemp + sDripIrrVolYr(i + 2 *
iNumHru)
        Else: End If
    End If
End If

sTotIrrVolSubYr(i) = (sTotIrrVolTemp * sArea(i - 1) * 100)
sTotIrrVolWatYr = sTotIrrVolWatYr + sTotIrrVolSubYr(i)
Next i

Open App.Path & "\\ModelOutputFiles\19_OptimalIrrVolHruYr.txt" For
Output As #19
Print #19, "Subbasin", "HRU", "IrrSys", "AnnualTotIrrVol"
Open App.Path & "\\ModelOutputFiles\19_OptVolSummary.txt" For Output
As #190
Open App.Path &
"\\ModelOutputFiles\19a_OptimalIrrVolCPivot_HruYr.txt" For Output As
#191
Print #191, "Subbasin", "HRU", "IrrSys", "AnnualTotIrrVol"
Open App.Path & "\\ModelOutputFiles\19b_OptimalIrrVolTGun_HruYr.txt"
For Output As #192
Print #192, "Subbasin", "HRU", "IrrSys", "AnnualTotIrrVol"
Open App.Path & "\\ModelOutputFiles\19c_OptimalIrrVolDrip_HruYr.txt"
For Output As #193
Print #193, "Subbasin", "HRU", "IrrSys", "AnnualTotIrrVol"
Open App.Path & "\\ModelOutputFiles\19_OptimalIrrVolHruYr_dbc.txt"
For Output As #194
Write #194, "Subbasin", "HRU", "IrrSys", "AnnualTotIrrVol"

For i = 1 To (iNumHru)
Print #19, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i),
sTotIrrVolSubYr(i)

```

```

    Write #194, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i),
sTotIrrVolSubYr(i)
    Print #191, iSubHruSum(i), iHruHruSum(i), "CPivot",
sCPivotIrrVolYr(i)
    Print #192, iSubHruSum(i), iHruHruSum(i), "TGun", sTGunIrrVolYr(i +
iNumHru)
    Print #193, iSubHruSum(i), iHruHruSum(i), "Drip", sDripIrrVolYr(i +
2 * iNumHru)

    sTotIrrVolCPivotYr = sTotIrrVolCPivotYr + (sCPivotIrrVolYr(i) *
sArea(i - 1) * 100)
    sTotIrrVolTGunYr = sTotIrrVolTGunYr + (sTGunIrrVolYr(i + iNumHru) *
sArea(i - 1) * 100)
    sTotIrrVolDripYr = sTotIrrVolDripYr + (sDripIrrVolYr(i + 2 *
iNumHru) * sArea(i - 1) * 100)

Next i

sAvgIrrVolWatYr = sTotIrrVolWatYr / (sTotAreaAgrrWat * 100)
sAvgIrrVolCPivotYr = sTotIrrVolCPivotYr / (sTotAreaAgrrWat * 100)
sAvgIrrVolTGunYr = sTotIrrVolTGunYr / (sTotAreaAgrrWat * 100)
sAvgIrrVolDripYr = sTotIrrVolDripYr / (sTotAreaAgrrWat * 100)

Print #19, " "
Print #19, " "
Print #19, " "
Print #19, " "
Print #19, "The Total Optimal Irrigation Volume Applied to the
Watershed is: ", sTotIrrVolWatYr
Print #19, "The average Optimal Irrigation Volume Applied per
Hectare is: ", sAvgIrrVolWatYr
Print #19, " "
Print #19, " "
Print #19, "The average Optimal Irrigation Volume Applied per
hectare using Center Pivot alone is: ", sAvgIrrVolCPivotYr
Print #19, "The average Optimal Irrigation Volume Applied per
hectare using Travelling Gun alone is: ", sAvgIrrVolTGunYr
Print #19, "The average Optimal Irrigation Volume Applied per
hectare using Drip alone is: ", sAvgIrrVolDripYr
Print #19, " "
Print #19, " "
Close #19

Write #190, sEconCWater(0), sAvgIrrVolWatYr, sAvgIrrVolCPivotYr,
sAvgIrrVolTGunYr, sAvgIrrVolDripYr
Close #190

Print #191, " "
Print #191, " "
Print #191, " "
Print #191, " "
Print #191, "The Total Optimal Irrigation Volume Applied to the
Watershed using Center Pivot System alone:", sTotIrrVolCPivotYr
Print #191, "The average Optimal Irrigation Volume Applied per
Hectare is:"; sAvgIrrVolCPivotYr
Print #191, " "

```

```

Print #191, " "
Print #191, " "
Print #191, " "
Close #191

Print #192, " "
Print #192, " "
Print #192, " "
Print #192, " "
Print #192, "The Total Optimal Irrigation Volume Applied to the
Watershed using Traveling Gun System alone:", sTotIrrVoltGunYr
Print #192, "The average Optimal Irrigation Volume Applied per
Hectare is:"; sAvgIrrVoltGunYr
Print #192, " "
Print #192, " "
Print #192, " "
Print #192, " "
Close #192

Print #193, " "
Print #193, " "
Print #193, " "
Print #193, " "
Print #193, "The Total Optimal Irrigation Volume Applied to the
Watershed using Drip Irrigation alone:", sTotIrrVolDripYr
Print #193, "The average Optimal Irrigation Volume Applied per
Hectare is:"; sAvgIrrVolDripYr
Print #193, " "
Print #193, " "
Print #193, " "
Print #193, " "
Close #193

Write #50, sAvgIrrVolWatYr, sAvgIrrVolCPivotYr, sAvgIrrVoltGunYr,
sAvgIrrVolDripYr
Close #50
iMsgVariable = MsgBox("All Calculations Have Been Completed",
vbOKOnly, "Program Message")
End Sub

'STEP 4: 2nd Level Call Procedures for DDS
'Net Benefit Comparison/Recommendations
Private Sub CompareNB IrrSys()
Dim i As Integer
Dim sTotNBWatYr As Single
Dim sTotNBCPivotYr As Single
Dim sTotNBTGunYr As Single
Dim sTotNBDripYr As Single
Dim sTempLineInput As String
Dim sAvgNBWatYr As Single
Dim sAvgNBCPivotYr As Single
Dim sAvgNBTGunYr As Single
Dim sAvgNBDripYr As Single

Call LoadNBVariables

```

```

    Open App.Path & "\\ModelOutputFiles\\18_SysRecommendations.txt" For
Output As #18
    Open App.Path & "\\ModelOutputFiles\\18_SysRecSummary.txt" For Output
As #180
    Open App.Path & "\\ModelOutputFiles\\18_SysRecommendations_dbc.txt"
For Output As #185
    Open App.Path & "\\ModelOutputFiles\\18a_CPivotRecommendations.txt"
For Output As #181
    Open App.Path & "\\ModelOutputFiles\\18b_TGunRecommendations.txt" For
Output As #182
    Open App.Path & "\\ModelOutputFiles\\18c_DripRecommendations.txt" For
Output As #183

```

```

    Print #18, "Subbasin", "HRU", "Optimal Irrig System",
"Recomendation", "Max. Ann. Net Benefit"
    Write #185, "Subbasin", "HRU", "Optimal Irrig System",
"Recomendation", "Net Benefit"
    Print #181, "Subbasin", "HRU", "CPivot Rec", "Max. Ann. Net
Benefit"
    Print #182, "Subbasin", "HRU", "TGun Rec", "Max. Ann. Net Benefit"
    Print #183, "Subbasin", "HRU", "Drip Rec", "Max. Ann. Net Benefit"

```

```

    Open App.Path & "\\ModelOutputFiles\\50_SAS_NB-OptVol_Data.txt" For
Output As #50
    Write #50, "Avg. NB Opt Sys", "Avg. NB CPivot", "Avg. NB TGun",
"Avg. NB Drip", "Avg. IrrVol Opt Sys", "Avg. IrrVol CPivot", "Avg.
IrrVol TGun", "Avg. IrrVol Drip"

```

```

sTotNBWatYr = 0
sTotNBCPivotYr = 0
sTotNBTGunYr = 0
sTotNBDripYr = 0

```

```

'The Following for loop initializes the recommended system to none.
For i = 1 To (iNumHru)
    sRecIrrSys(i) = "Irrigation Not Recommended"
    iRecIrrSysInt(i) = 99
Next i

```

```

For i = 1 To (iNumHru)

```

```

'The following 'If Then' statements determine if irrigation is
Recommended.

```

```

If sCPivotNBDifYr(i) > 0 Then
    bCPivotRecYr(i) = True
Else: bCPivotRecYr(i) = False
End If
sTotNBCPivotYr = sTotNBCPivotYr + (sCPivotNBDifYr(i) * sArea(i - 1)
* 100)

```

```

Print #181, iSubHruSum(i), iHruHruSum(i), bCPivotRecYr(i),
sCPivotNBDifYr(i)

```

```

If sTGunNBDifYr(i + iNumHru) > 0 Then
    bTGunRecYr(i) = True

```



```

Else: bTGunRecYr(i) = False
End If
sTotNBTGunYr = sTotNBTGunYr + (sTGunNBDifYr(i + iNumHru) * sArea(i
- 1) * 100)

Print #182, iSubHruSum(i), iHruHruSum(i), bTGunRecYr(i),
sTGunNBDifYr(i + iNumHru)

If sDripNBDifYr(i + 2 * iNumHru) > 0 Then
    bDripRecYr(i) = True
Else: bDripRecYr(i) = False
End If
sTotNBDripYr = sTotNBDripYr + (sDripNBDifYr(i + 2 * iNumHru) *
sArea(i - 1) * 100)

Print #183, iSubHruSum(i), iHruHruSum(i), bDripRecYr(i),
sDripNBDifYr(i + 2 * iNumHru)

'The following 'if then' statements determine which irrigation
system has the greatest net benefit.

If (sCPivotNBDifYr(i) > sTGunNBDifYr(i + iNumHru)) And
(sCPivotNBDifYr(i) > sDripNBDifYr(i + 2 * iNumHru)) Then
    sRecIrrSys(i) = "Center Pivot System"
    iRecIrrSysInt(i) = 0
    sNBMaxDif(i) = sCPivotNBDifYr(i)
Else:
    If (sTGunNBDifYr(i + iNumHru) > sCPivotNBDifYr(i)) And
(sTGunNBDifYr(i + iNumHru) > sDripNBDifYr(i + 2 * iNumHru)) Then

        sRecIrrSys(i) = "Travelling Gun System"
        iRecIrrSysInt(i) = 1
        sNBMaxDif(i) = sTGunNBDifYr(i + iNumHru)
    Else:
        If (sDripNBDifYr(i + 2 * iNumHru) > sCPivotNBDifYr(i)) And
(sDripNBDifYr(i + 2 * iNumHru) > sTGunNBDifYr(i + iNumHru)) Then
            sRecIrrSys(i) = "Drip Irrigation System"
            iRecIrrSysInt(i) = 2
            sNBMaxDif(i) = sDripNBDifYr(i + 2 * iNumHru)
        Else:
            End If
        End If
    End If
End If

sTotNBWatYr = sTotNBWatYr + (sNBMaxDif(i) * sArea(i - 1) * 100)

If sNBMaxDif(i) > 0 Then
Write #18, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i), "Irrig.
Recommended", sNBMaxDif(i)
Write #185, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i), "Irrig.
Recommended", sNBMaxDif(i)
Else:
Write #18, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i), "Irrig. Not
Rec.", sNBMaxDif(i)

```

```

Write #185, iSubHruSum(i), iHruHruSum(i), sRecIrrSys(i), "Irrig.
Not Rec.", sNBMaxDif(i)
End If
Next i

sAvgNBWatYr = sTotNBWatYr / (sTotAreaAgrrWat * 100)
sAvgNBCPivotYr = sTotNBCPivotYr / (sTotAreaAgrrWat * 100)
sAvgNBTGunYr = sTotNBTGunYr / (sTotAreaAgrrWat * 100)
sAvgNBDripYr = sTotNBDripYr / (sTotAreaAgrrWat * 100)

Print #18, " "
Print #18, " "
Print #18, " "
Print #18, " "
Print #18, "The Total Net Benefit for the entire Watershed is:",
sTotNBWatYr
Print #18, "The Average Net Benefit for all HRU's per Hectare is:",
sAvgNBWatYr
Print #18, " "
Print #18, "The Average Net Benefit for all HRU's within the
watershed weighted equally (Using a Center Pivot System) is:",
sAvgNBCPivotYr
Print #18, "The Average Net Benefit for all HRU's within the
watershed weighted equally (Using a Travelling Gun System) is:",
sAvgNBTGunYr
Print #18, "The Average Net Benefit for all HRU's within the
watershed weighted equally (Using Drip Irrigation) is:", sAvgNBDripYr
Print #18, " "
Print #18, " "
Print #18, " "

Write #180, sEconCWater(0), sAvgNBWatYr, sAvgNBCPivotYr,
sAvgNBTGunYr, sAvgNBDripYr

Print #181, " "
Print #181, " "
Print #181, " "
Print #181, " "
Print #181, "The Total Net Benefit for the entire Watershed using
CenterPivot Irrigation is:", sTotNBCPivotYr
Print #181, "The Average Net Benefit for all HRU's within the
watershed weighted equally is:", sAvgNBCPivotYr
Print #181, " "
Print #181, " "
Print #181, " "
Print #181, " "

Print #182, " "
Print #182, " "
Print #182, " "
Print #182, " "
Print #182, "The Total Net Benefit for the entire Watershed using
TravellingGun Irrigation is:", sTotNBTGunYr
Print #182, "The Average Net Benefit for all HRU's within the
watershed weighted equally is:", sAvgNBTGunYr
Print #182, " "

```

```

Print #182, " "
Print #182, " "
Print #182, " "

Print #183, " "
Print #183, " "
Print #183, " "
Print #183, " "
Print #183, "The Total Net Benefit for the entire Watershed using
Drip Irrigation is:", sTotNBDripYr
Print #183, "The Average Net Benefit for all HRU's within the
watershed weighted equally is:", sAvgNBDripYr
Print #183, " "
Print #183, " "
Print #183, " "
Print #183, " "

Write #50, sAvgNBWatYr, sAvgNBCPivotYr, sAvgNBTGunYr, sAvgNBDripYr

Close #18
Close #180
Close #181
Close #182
Close #183
Close #185
Close #20
End Sub

```

```

'STEP 4: 3rd Level Call Procedures for DDS
Public Sub LoadNBVariables()
    Dim iIrrCtrTemp As Integer 'variable used to determine irrigation
system information being read
    Dim iHruTemp As Integer
    Dim sIrrSysTemp As String
    Dim sNBWOITemp, sNBWITemp, sNBDifTemp, sIrrVolTemp As Single
    Dim i As Integer 'for loop counter
    Dim j As Integer 'for iHruNum Counter
    Dim iNBFileLength As Long
    Dim sInputLine As String

    Call OpenGenInputPrintFiles

    For i = 1 To (3 * iNumHru)
        If EOF(21) = False Then
            Input #21, iIrrCtrTemp, iHruTemp, sIrrSysTemp, sNBWOITemp,
sNBWITemp, sNBDifTemp, sIrrVolTemp
            Else: End If

            If iIrrCtrTemp = 0 Then
                sCPivotNBWOIYr(i) = sNBWOITemp
                sCPivotNBWIYr(i) = sNBWITemp
                sCPivotNBDifYr(i) = sNBDifTemp
                sCPivotIrrVolYr(i) = sIrrVolTemp
                If sNBDifTemp <> 0 Then
                    bCPivotRecYr(i) = True
                Else: bCPivotRecYr(i) = False
                End If
            End If
        End For
    End Sub

```

```

Else: End If

If iIrrCtrTemp = 1 Then
    sTGunNBWOIYr(i) = sNBWOITemp
    sTGunNBWIIYr(i) = sNBWITemp
    sTGunNBDifYr(i) = sNBDifTemp
    sTGunIrrVolYr(i) = sIrrVolTemp
    If sNBDifTemp <> 0 Then
        bTGunRecYr(i) = True
    Else: bTGunRecYr(i) = False
    End If
Else: End If

If iIrrCtrTemp = 2 Then
    sDripNBWOIYr(i) = sNBWOITemp
    sDripNBWIIYr(i) = sNBWITemp
    sDripNBDifYr(i) = sNBDifTemp
    sDripIrrVolYr(i) = sIrrVolTemp
    If sNBDifTemp <> 0 Then
        bDripRecYr(i) = True
    Else: bDripRecYr(i) = False
    End If
Else: End If

Next i

    Open App.Path & "\ModelOutputFiles\20_NBCalcTempFile.txt" For
Output As #20
    For i = 1 To iNumHru
        Print #20, iHru(i - 1), sCPivotNBWIIYr(i), sCPivotNBWOIYr(i),
sCPivotNBDifYr(i), sTGunNBWIIYr(i + iNumHru), sTGunNBWOIYr(i + iNumHru),
sTGunNBDifYr(i + iNumHru), sDripNBWIIYr(i + 2 * iNumHru), sDripNBWOIYr(i
+ 2 * iNumHru), sDripNBDifYr(i + 2 * iNumHru)
    Next i

    Close #21
End Sub

'Menu Items
'Step 1:
Private Sub mnuSelectEcon_Click()
    Call cmdEconSelect_Click
End Sub

Private Sub mnuSelectIrrig_Click()
    Call cmdIrrSelect_Click
End Sub

Private Sub mnuSelectSwat_Click()
    Call cmdSwatSelect_Click
End Sub

'Step 2:
Private Sub mnuEditEcon_Click()
    Call cmdViewEconData_Click

```

```

End Sub

Private Sub mnuEditIrrig_Click()
    Call cmdViewIrrigData_Click
End Sub

Private Sub mnuEditSwat_Click()
    Call cmdViewSwatData_Click
End Sub

'Step 3:
Private Sub mnuNBAll_Click()
    Call cmdNB_All_Click
End Sub

Private Sub mnuNBCPivot_Click()
    Call cmdNB_1_Click
End Sub

Private Sub mnuNBDrip_Click()
    Call cmdNB_3_Click
End Sub

Private Sub mnuNBTGun_Click()
    Call cmdNB_2_Click
End Sub

'Step 4:
Private Sub mnuViewSysRec_Click()
    Call cmdRecommendations_Click
End Sub

Private Sub mnuViewIrrigD_Click()
    Call cmdIrrVol_Click
End Sub

```

## Appendix G: ANOVA Results on Full list of SWAT Variables

Table 48, Table 49 and Table 50 include a full listing of economic, SWAT and soils data variables for which an ANOVA was performed using the irrigation application, maximum net benefit and the recommended irrigation system as the dependent variables, respectively.

**Table 48.** Full listing of analysis of variance (ANOVA) results obtained in determining the factors correlated to model irrigation system recommendation.

Model Variable	Variable Description	Num. DF	Den. DF	F-Value	Associated Probability
<b><i>Economic Parameters:</i></b>					
WaterCost	Cost of water per unit volume	1	8671	2446.62	<0.0001
Ky	Crop response factor	1	8671	28.19	<0.0001
IrrInsCost	Irrigation Installation Costs	1	8671	949.17	<0.0001
IrrMainCost	Irrigation Maintenance Costs	1	8671	949.17	<0.0001
IrrigEff	Irrigation Distribution Efficiency	1	8671	949.17	<0.0001
<b><i>.SBS SWAT Parameters</i></b>					
SUB	Topographically defined subbasin	78	8594	1.80	<0.0001
HRU	Hydrologic response unit	1	8671	21.45	<0.0001
LULC	Land cover/plant associated with HRU	6	8666	947.65	<0.0001
AREA	Drainage area of the HRU	1	6547	0.51	0.4772
PRECIP	Precipitation falling on HRU	1	6547	32.03	<0.0001
SNOFALL	Precipitation falling as snow	1	6547	2.43	0.1191
SNOMELT	Amount of snow/ice melting in time step	1	6547	2.20	0.1381
PET	Potential evapotranspiration	1	6547	20.89	<0.0001
ET	Actual evapotranspiration	1	6547	251.16	<0.0001
SW	Soil water content	1	6547	317.92	<0.0001
PERC	Water that percolates past the root zone during the time step	1	6547	67.88	<0.0001
GWRCHG	Total recharge entering shallow and deep aquifer	1	6547	68.07	<0.0001
DARCHG	Deep aquifer recharge	1	6547	59.63	<0.0001
REVAP	Water in the shallow aquifer entering the root zone	1	6547	108.33	<0.0001
SAST	Shallow aquifer storage	1	6547	16.60	<0.0001
DAST	Deep aquifer storage	1	6547	57.86	<0.0001
SURQ	Surface runoff contributing to stream flow	1	6547	334.26	<0.0001
TLOSS	Water lost from tributary channels via the channel bed	1	6547	44.55	<0.0001
LATQ	Lateral flow contributing to	1	6547	75.04	<0.0001

	streamflow				
GWQ	Groundwater contribution to streamflow	1	6547	67.81	<0.0001
WYLD	Total water leaving the HRU	1	6547	184.21	<0.0001
SYLD	Sediment from the HRU transported into the main channel	1	6547	241.73	<0.0001
USLE	Soil loss during the time step	1	6547	179.20	<0.0001
NAPP	Nitrogen fertilizer applied	1	6547	458.44	<0.0001
PAPP	Phosphorus fertilizer applied	1	6547	458.44	<0.0001
NRAIN	Nitrate added to the soil profile by rain	1	6547	36.70	<0.0001
NFIX	Nitrogen fixed by legumes	1	6547	125.36	<0.0001
FMN	Mineralization of nitrogen to nitrate and active organic nitrogen	1	6547	1675.52	<0.0001
AMN	Active organic mineral nitrogen	1	6547	137.77	<0.0001
ASN	Conversion of active nitrogen to stable organic nitrogen	1	6547	100.96	<0.0001
FMP	Mineralization of phosphorus to active mineral and organic pool	1	6547	2722.22	<0.0001
AOLP	Movement of phosphorus from organic pool to the liable mineral pool during time step	1	6547	146.84	<0.0001
LAP	Labile to active mineral phosphorus	1	6547	533.62	<0.0001
ASP	Active to stable phosphorus	1	6547	554.40	<0.0001
DNIT	Denitrification, transformation of nitrate to gaseous compounds	1	6547	556.17	<0.0001
NUP	Plant uptake of nitrogen	1	6547	949.71	<0.0001
PUP	Plant uptake of phosphorus	1	6547	1519.21	<0.0001
ORGN	Nitrogen transported out of HRU	1	6547	108.11	<0.0001
ORGP	Phosphorus transported out of HRU	1	6547	89.12	<0.0001
SEDP	Mineral phosphorus transported into reach with sediment	1	6547	251.57	<0.0001
NSURQ	Nitrate in surface runoff	1	6547	402.07	<0.0001
NLATQ	Nitrate in lateral flow	1	6547	556.59	<0.0001
NO3L	Nitrate leached from the soil profile	1	6547	46.38	<0.0001
SOLP	Soluble phosphorus in runoff	1	6547	1538.30	<0.0001
WSTRS	Water stress days	1	6547	999.87	<0.0001
TMPSTRS	Temperature stress days	1	6547	88.45	<0.0001
NSTRS	Nitrogen stress days	1	6547	131.69	<0.0001
PSTRS	Phosphorus stress days	1	6547	2544.48	<0.0001
BIOM	Total biomass of plant material	1	6547	1084.11	<0.0001
LAI	Leaf area index	1	6547	1806.88	<0.0001
YLD	Harvested yield	1	6547	48.00	<0.0001
<b>Soil Parameters:</b>					
SoilType	Soil type	11	8661	12.40	<0.0001
Ldepth	Top soil layer depth	1	8671	25.80	<0.0001
AWC	Available water capacity of the soil layer	1	8671	34.86	<0.0001

HydCond	Hydraulic conductivity of top soil layer	1	8671	10.80	0.0010
pClay	Percent clay content of top soil layer	1	8671	101.49	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	29.65	<0.0001
pSand	Percent sand content of top soil layer	1	8671	43.81	<0.0001
Ldepth2	Soil layer depth of second soil layer	1	8671	15.10	0.0001
AWC2	Available water capacity of second soil layer	1	8671	89.43	<0.0001
HydCond2	Hydraulic conductivity of second soil layer	1	8671	19.06	<0.0001
pClay2	Percent clay content of second soil layer	1	8671	46.94	<0.0001
pSilt2	Percent silt content of second soil layer	1	8671	110.01	<0.0001
pSand2	Percent sand content of second soil layer	1	8671	99.33	<0.0001
<b>HRU Parameters:</b>					
MinElev	Lowest elevation point within HRU	1	8671	6.51	0.0107
MaxElev	Highest elevation point within HRU	1	8671	8.43	0.0037
MeanElev	Average elevation of HRU	1	8671	9.54	0.0020

**Table 49.** Full listing of analysis of variance (ANOVA) results obtained in determining the factors correlated to model calculated maximum net benefit of irrigation.

Model Variable	Variable Description	Num. DF	Den. DF	F-Value	Associated Probability
<b>Economic Parameters:</b>					
WaterCost	Cost of water per unit volume	1	8671	5122.72	<0.0001
Ky	Crop response factor	1	8671	6.78	0.0092
IrrInsCost	Irrigation Installation Costs	1	8671	17.10	<0.0001
IrrMainCost	Irrigation Maintenance Costs	1	8671	17.10	<0.0001
IrrigEff	Irrigation Distribution Efficiency	1	8671	17.10	<0.0001
<b>.SBS SWAT Parameters</b>					
SUB	Topographically defined subbasin	78	8594	2.23	<0.0001
HRU	Hydrologic response unit	1	8671	43.77	<0.0001
LULC	Land cover/plant associated with HRU	6	8666	1239.87	<0.0001
AREA	Drainage area of the HRU	1	6547	0.55	0.4589
PRECIP	Precipitation falling on HRU	1	6547	47.25	<0.0001
SNOFALL	Precipitation falling as snow	1	6547	2.43	0.1192
SNOMELT	Amount of snow/ice melting in time step	1	6547	2.65	0.1036
PET	Potential evapotranspiration	1	6547	0.24	0.6242
ET	Actual evapotranspiration	1	6547	471.34	<0.0001
SW	Soil water content	1	6547	727.57	<0.0001



PERC	Water that percolates past the root zone during the time step	1	6547	86.65	<0.0001
GWRCHG	Total recharge entering shallow and deep aquifer	1	6547	86.76	<0.0001
DARCHG	Deep aquifer recharge	1	6547	79.01	<0.0001
REVAP	Water in the shallow aquifer entering the root zone	1	6547	112.21	<0.0001
SAST	Shallow aquifer storage	1	6547	40.44	<0.0001
DAST	Deep aquifer storage	1	6547	77.81	<0.0001
SURQ	Surface runoff contributing to stream flow	1	6547	241.71	<0.0001
TLOSS	Water lost from tributary channels via the channel bed	1	6547	36.96	<0.0001
LATQ	Lateral flow contributing to streamflow	1	6547	17.37	<0.0001
GWQ	Groundwater contribution to streamflow	1	6547	86.61	<0.0001
WYLD	Total water leaving the HRU	1	6547	352.29	<0.0001
SYLD	Sediment from the HRU transported into the main channel	1	6547	219.15	<0.0001
USLE	Soil loss during the time step	1	6547	239.29	<0.0001
NAPP	Nitrogen fertilizer applied	1	6547	106.48	<0.0001
PAPP	Phosphorus fertilizer applied	1	6547	106.48	<0.0001
NRAIN	Nitrate added to the soil profile by rain	1	6547	51.70	<0.0001
NFIX	Nitrogen fixed by legumes	1	6547	338.90	<0.0001
FMN	Mineralization of nitrogen to nitrate and active organic nitrogen	1	6547	1918.89	<0.0001
AMN	Active organic mineral nitrogen	1	6547	174.36	<0.0001
ASN	Conversion of active nitrogen to stable organic nitrogen	1	6547	114.79	<0.0001
FMP	Mineralization of phosphorus to active mineral and organic pool	1	6547	6582.01	<0.0001
AOLP	Movement of phosphorus from organic pool to the liable mineral pool during time step	1	6547	212.16	<0.0001
LAP	Labile to active mineral phosphorus	1	6547	139.48	<0.0001
ASP	Active to stable phosphorus	1	6547	155.84	<0.0001
DNIT	Denitrification, transformation of nitrate to gaseous compounds	1	6547	225.61	<0.0001
NUP	Plant uptake of nitrogen	1	6547	732.19	<0.0001
PUP	Plant uptake of phosphorus	1	6547	2652.02	<0.0001
ORGN	Nitrogen transported out of HRU	1	6547	202.02	<0.0001
ORGP	Phosphorus transported out of HRU	1	6547	161.06	<0.0001
SEDP	Mineral phosphorus transported into reach with sediment	1	6547	69.08	<0.0001
NSURQ	Nitrate in surface runoff	1	6547	525.47	<0.0001
NLATQ	Nitrate in lateral flow	1	6547	254.74	<0.0001
NO3L	Nitrate leached from the soil profile	1	6547	71.12	<0.0001

SOLP	Soluble phosphorus in runoff	1	6547	1833.16	<0.0001
WSTRS	Water stress days	1	6547	3276.03	<0.0001
TMPSTRS	Temperature stress days	1	6547	1300.60	<0.0001
NSTRS	Nitrogen stress days	1	6547	43.56	<0.0001
PSTRS	Phosphorus stress days	1	6547	1374.88	<0.0001
BIOM	Total biomass of plant material	1	6547	886.36	<0.0001
LAI	Leaf area index	1	6547	1116.38	<0.0001
YLD	Harvested yield	1	6547	114.31	<0.0001
<b>Soil Parameters:</b>					
SoilType	Soil type	11	8661	13.37	<0.0001
Ldepth	Top soil layer depth	1	8671	53.61	<0.0001
AWC	Available water capacity of the soil layer	1	8671	16.81	<0.0001
HydCond	Hydraulic conductivity of top soil layer	1	8671	9.08	0.0026
pClay	Percent clay content of top soil layer	1	8671	103.49	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	13.26	0.0003
pSand	Percent sand content of top soil layer	1	8671	25.49	<0.0001
Ldepth2	Soil layer depth of second soil layer	1	8671	31.34	<0.0001
AWC2	Available water capacity of second soil layer	1	8671	95.87	<0.0001
HydCond2	Hydraulic conductivity of second soil layer	1	8671	33.98	<0.0001
pClay2	Percent clay content of second soil layer	1	8671	86.60	<0.0001
pSilt2	Percent silt content of second soil layer	1	8671	113.46	<0.0001
pSand2	Percent sand content of second soil layer	1	8671	120.37	<0.0001
<b>HRU Parameters:</b>					
MinElev	Lowest elevation point within HRU	1	8671	19.74	<0.0001
MaxElev	Highest elevation point within HRU	1	8671	20.67	<0.0001
MeanElev	Average elevation of HRU	1	8671	23.54	<0.0001

**Table 50.** Full listing of analysis of variance (ANOVA) results obtained in determining the factors correlated to the model recommended irrigation system.

Model Variable	Variable Description	Num. DF	Den. DF	F-Value	Associated Probability
<b>Economic Parameters:</b>					
WaterCost	Cost of water per unit volume	1	8671	1333.00	<0.0001
Ky	Crop response factor	1	8671	0.48	0.4881
IrrInsCost	Irrigation Installation Costs	1	8671	Infinity	<0.0001
IrrMainCost	Irrigation Maintenance Costs	1	8671	Infinity	<0.0001
IrrigEff	Irrigation Distribution Efficiency	1	8671	Infinity	<0.0001
<b>.SBS SWAT Parameters</b>					
SUB	Topographically defined	78	8594	3.04	<0.0001

	subbasin				
HRU	Hydrologic response unit	1	8671	29.38	<0.0001
LULC	Land cover/plant associated with HRU	6	8666	486.50	<0.0001
AREA	Drainage area of the HRU	1	6547	3.01	0.0828
PRECIP	Precipitation falling on HRU	1	6547	20.15	<0.0001
SNOFALL	Precipitation falling as snow	1	6547	0.52	0.4728
SNOMELT	Amount of snow/ice melting in time step	1	6547	0.58	0.4470
PET	Potential evapotranspiration	1	6547	0.76	0.3843
ET	Actual evapotranspiration	1	6547	46.95	<0.0001
SW	Soil water content	1	6547	266.30	<0.0001
PERC	Water that percolates past the root zone during the time step	1	6547	60.08	<0.0001
GWRCHG	Total recharge entering shallow and deep aquifer	1	6547	60.15	<0.0001
DARCHG	Deep aquifer recharge	1	6547	56.52	<0.0001
REVAP	Water in the shallow aquifer entering the root zone	1	6547	59.82	<0.0001
SAST	Shallow aquifer storage	1	6547	35.27	<0.0001
DAST	Deep aquifer storage	1	6547	55.90	<0.0001
SURQ	Surface runoff contributing to stream flow	1	6547	95.76	<0.0001
TLOSS	Water lost from tributary channels via the channel bed	1	6547	10.47	0.0012
LATQ	Lateral flow contributing to streamflow	1	6547	41.38	<0.0001
GWQ	Groundwater contribution to streamflow	1	6547	59.92	<0.0001
WYLD	Total water leaving the HRU	1	6547	26.50	<0.0001
SYLD	Sediment from the HRU transported into the main channel	1	6547	67.60	<0.0001
USLE	Soil loss during the time step	1	6547	46.66	<0.0001
NAPP	Nitrogen fertilizer applied	1	6547	316.44	<0.0001
PAPP	Phosphorus fertilizer applied	1	6547	316.44	<0.0001
NRAIN	Nitrate added to the soil profile by rain	1	6547	22.09	<0.0001
NFIX	Nitrogen fixed by legumes	1	6547	125.36	<0.0001
FMN	Mineralization of nitrogen to nitrate and active organic nitrogen	1	6547	709.20	<0.0001
AMN	Active organic mineral nitrogen	1	6547	47.57	<0.0001
ASN	Conversion of active nitrogen to stable organic nitrogen	1	6547	65.20	<0.0001
FMP	Mineralization of phosphorus to active mineral and organic pool	1	6547	676.80	<0.0001
AOLP	Movement of phosphorus from organic pool to the liable mineral pool during time step	1	6547	43.80	<0.0001
LAP	Labile to active mineral phosphorus	1	6547	415.11	<0.0001
ASP	Active to stable phosphorus	1	6547	438.20	<0.0001
DNIT	Denitrification, transformation	1	6547	327.73	<0.0001

	of nitrate to gaseous compounds				
NUP	Plant uptake of nitrogen	1	6547	388.91	<0.0001
PUP	Plant uptake of phosphorus	1	6547	289.84	<0.0001
ORGN	Nitrogen transported out of HRU	1	6547	27.63	<0.0001
ORGP	Phosphorus transported out of HRU	1	6547	56.19	<0.0001
SEDP	Mineral phosphorus transported into reach with sediment	1	6547	142.74	<0.0001
NSURQ	Nitrate in surface runoff	1	6547	175.54	<0.0001
NLATQ	Nitrate in lateral flow	1	6547	293.44	<0.0001
NO3L	Nitrate leached from the soil profile	1	6547	45.44	<0.0001
SOLP	Soluble phosphorus in runoff	1	6547	773.11	<0.0001
WSTRS	Water stress days	1	6547	581.77	<0.0001
TMPSTRS	Temperature stress days	1	6547	94.31	<0.0001
NSTRS	Nitrogen stress days	1	6547	17.12	<0.0001
PSTRS	Phosphorus stress days	1	6547	501.89	<0.0001
BIOM	Total biomass of plant material	1	6547	902.60	<0.0001
LAI	Leaf area index	1	6547	809.25	<0.0001
YLD	Harvested yield	1	6547	230.78	<0.0001
<b>Soil Parameters:</b>					
SoilType	Soil type	11	8661	23.08	<0.0001
Ldepth	Top soil layer depth	1	8671	35.23	<0.0001
AWC	Available water capacity of the soil layer	1	8671	95.98	<0.0001
HydCond	Hydraulic conductivity of top soil layer	1	8671	29.73	<0.0001
pClay	Percent clay content of top soil layer	1	8671	194.86	<0.0001
pSilt	Percent silt content of top soil layer	1	8671	71.47	<0.0001
pSand	Percent sand content of top soil layer	1	8671	99.43	<0.0001
Ldepth2	Soil layer depth of second soil layer	1	8671	26.84	<0.0001
AWC2	Available water capacity of second soil layer	1	8671	173.09	<0.0001
HydCond2	Hydraulic conductivity of second soil layer	1	8671	42.50	<0.0001
pClay2	Percent clay content of second soil layer	1	8671	70.82	<0.0001
pSilt2	Percent silt content of second soil layer	1	8671	190.91	<0.0001
pSand2	Percent sand content of second soil layer	1	8671	166.65	<0.0001
<b>HRU Parameters:</b>					
MinElev	Lowest elevation point within HRU	1	8671	7.08	0.0078
MaxElev	Highest elevation point within HRU	1	8671	14.13	0.0002
MeanElev	Average elevation of HRU	1	8671	13.79	0.0002



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