# ABSTRACT

Title of Thesis: A COMPARATIVE HYDROLOGIC ANALYSIS OF SURFACE MINED AND FORESTED WATERSHEDS IN WESTERN MARYLAND.

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This thesis presents the results of a hydrologic analysis conducted as part of a larger, multi-faceted, collaborative effort to study ecosystem function of a watershed subjected to surface mining and reclamation in the Appalachian Region of the United States. The primary goal of this study was to determine whether a small watershed subjected to surface mine reclamation practices (MAT1) displayed a stormflow response to rain events that was different from those displayed by a young second-growth forested watershed (NEF1). A secondary goal was to investigate whether intensive surface mining in the Georges Creek basin has altered stormflow response at a larger river basin scale when compared to a similar, but predominantly forested basin (Savage River). At the small watersheds, MAT1 produced greater a) runoff coefficients (2.5x); b) total

runoff (3x); and c) peak runoff rates (2x) compared to NEF1. Total rainfall explained 63% of the variation in total runoff at MAT1 compared to only 21% of the variation in total runoff at NEF1. Regardless of a recent 13% increase in surface mine reclamation in the Georges Creek basin, little difference in stormflow response was observed for 15 storms analyzed across the two larger basins. Georges Creek on average responded 3 hr more quickly than Savage River, However the hydrological response characteristics of the two basins were similar. In addition, hydrological response characteristics for Georges Creek and Savage River remained relatively stable over time. Further research is needed to address inabilities to scale responses observed at the small watersheds.

# A COMPARATIVE HYDROLOGIC ANALYSIS OF SURFACE MINED AND FORESTED WATERSHEDS IN WESTERN MARYLAND.

by

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# Chapter I: INTRODUCTION

The relationship between land use and land cover (LULC) and the hydrologic response of watersheds is becoming highly scrutinized in science, management, and public policy. In the majority of studies, the effects of deforestation, agriculture, urbanization, and wetland drainage have been examined. The watershed is frequently chosen as the basic unit of study for examining the effects of LULC change because watersheds have a definable hydrologic boundary; the area within the watershed boundary can be thought of as a "black box" where the difference between inputs and outputs are stored within the system. However, disturbance occurring within the system has the potential to alter the hydrologic responsiveness of watersheds (Freeze 1974). In the majority of studies of LULC change, hydrologic response characteristics such as changes in peak stormflow, flood frequency, and rainfall/runoff ratios have been examined.

A number of studies have investigated the hydrological effects of timber harvesting (Hornbeck et al. 1970, Swift et al. 1975, Burt and Swank 1992, Jones and Grant 1996, Burton 1997, Kochenderfer et al. 1997, Thomas and Megahan 1998), urbanization and suburbanization ( Burges et al. 1998, Rose and Peters in press), and changes in agricultural areas and practices (Gebert and Krug 1996, Kuhnle et al. 1996, Allan et al. 1997, Mwendera and Mohamed-Saleem 1997). Changes in LULC often involve altering the land cover through intensive vegetation removal. Hornbeck et al. (1970), Burton (1997), and others have observed that intensive removal of vegetation can significantly increase runoff and flooding hazards. Most often, streamflow changes have been attributed to changes in evapotranspiration rates (Swift et al. 1975, Gifford et. al. 1984, Swanson 1984, Troendle and King 1987). Implementation of best management practices such as proper road design on logged lands can reduce the effects of timber harvesting (Kochenderfer et al. 1997, Thomas and Megahan 1998). In addition, Burt and Swank (1992) provide some evidence that as a forest regenerates it can exhibit evapotranspiration rates as high as dense grass. All of these studies suggest a strong relationship between land use change and watershed response, however.

Another specific type of land use change that disturbs many of the physical properties of a watershed is the extraction of bituminous coal via surface mining. Surface mining and subsequent land reclamation has become widespread in the Appalachian region of the United States since the early 1950's (J. Carey, Maryland Bureau of Mines, personal communication) with the advent of large earthmovers. Under the Surface Mine Control and Reclamation Act of 1977 (SMCRA, PL 95-87) mine operators are obligated to reclaim surface mined lands to the approximate original contours and to acceptable LULC. The overall process involves extracting the material, or overburden, that overlies the coal seam. The topsoil is retained in a separate pile. Following coal extraction, the overburden is replaced, graded to the approximate original contour using large earthmovers, and typically seeded with grasses. A common result of reclamation is minesoils that are highly compacted (Bussler et al. 1984, McSweeney and Jansen 1984, Bell et al. 1994, Chong and Cowsert 1997).

The Georges Creek watershed in western Maryland is an example of a watershed that has undergone intensive surface mining. Catastrophic flooding in the Georges Creek watershed in June of 1995 and January of 1996 led to speculation that surface mining and reclamation has altered the hydrologic response of the watershed and increased the potential for damaging floods and associated economic losses. In addition to the economic losses caused by flooding, increased flooding frequency can have deleterious effects on stream biota. However, in the Georges Creek watershed as elsewhere, the effects of this LULC change on watershed stormflow response are poorly understood and empirical data on this phenomenon are essentially non-existent.

A limited number of studies have investigated the hydrological effects of surface mining and reclamation on watershed stormflow response, but essentially no research has focused on the long-term cumulative impacts of mine reclamation distributed throughout a watershed. In theory, watersheds subjected to mine reclamation may respond similar to those having undergone urbanization/suburbanization, as both activities act to decrease the perviousness of the landscape. Most imperviousness on reclaimed surface mines is the result of massive compaction (Bussler et al. 1984, McSweeney and Jansen 1984, Bell et al. 1994, Chong and Cowsert 1997). Compaction has been shown to substantially reduce infiltration rates (Barnhisel and Hower 1997) and essentially eliminate the macropore networks (Dunker et al. 1995) that increase infiltration capacities (Beven and Germann 1982). Mine reclamation can also disturb water table elevations and subsurface flow paths (Bonta et al. 1992). Ritter and Gardner (1993) observed that on newly reclaimed mine lands in Pennsylvania, infiltration-excess overland flow is the dominant runoff process. Likewise Bonta et al. (1997) observed increased peak streamflow rates in response to mine reclamation. It could be argued that the limited data available for the pre-mining period, however, were insufficient to compare pre- and post-mining impacts.

The unit hydrograph technique is one method that could help quantify the effects of strip mine reclamation. The method was first outlined by Sherman (1932) and is still widely used in hydrological studies (Chapman 1996a, b, Dietrich 1996, Sefton and Boorman 1997), particularly in urban planning. The unit hydrograph of a watershed is defined as the hydrograph of one unit (inch or cm) of storm runoff generated by a rainstorm of uniform intensity and distribution occurring within a specific period of time (Dunne and Leopold 1978). Unit hydrographs are conducive to investigating hydrological effects of LULC change because in theory they are affected by a) rainfall characteristics and b) watershed characteristics. For small watersheds on the order of 1 $km^2$ or less, many of the watershed characteristics are fixed from storm to storm (e.g., watershed area, topography, channel morphology, LULC, and soil properties). Therefore, one might expect that storms with similar rainfall characteristics (similar depth and intensity) would produce similar unit hydrographs. For larger watersheds on the order of 100 $km^2$, however, the necessary assumption that a rain event is uniformly distributed over the watershed is usually difficult to achieve. Physiographic features, such as LULC, can change appreciably over relatively short time periods (~50 years). Based on unit hydrograph theory, if variations in rainfall characteristics can be minimized between watersheds and among the set of storms being analyzed, then differences in unit hydrograph shape could only be attributed to changes in physical watershed characteristics (e.g., LULC).

Numerous methods exist for calculating unit hydrographs by deconvolution (Snyder 1938, Langbein 1940, Rantz 1971, US Soil Conservation Service 1972), one of which is the relatively simple $\Phi$-index technique. The $\Phi$-index method produces an estimate of the excess rainfall hyetograph by assuming a constant rate of rainfall "abstraction" (that fraction of the rainfall that does not contribute to stormflow) represented by $\Phi$ (Figure 1A). By definition, the excess rainfall is that portion of total rainfall that produces direct runoff. A more sophisticated approach is used by PC-IHACRES (identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data) developed by Littlewood et al. (1997). IHACRES is a rainfall-runoff model that uses a) a non-linear loss module to determine effective rainfall and b) a linear loss module to develop a unit hydrograph used for estimating streamflow (Figure 1B). The main advantage of using IHACRES is its spatially 'lumped' approach (Figure 2); the sole data requirements are continuous time series of rainfall, streamflow, and air temperature (although the model can be calibrated without air temperature). A large number of studies published in the literature have applied and successfully calibrated IHACRES over a wide range of spatio-temporal conditions (Chiew et al. 1993, Hansen et al. 1996, Schreider et al. 1996, Andreassian et al. 2001, Kokkonen et al. 2001, Letcher et al. 2001, Schreider et al. 2001). The model produces reasonable estimates of unit hydrographs over watersheds ranging from 490 $km^2$ to 10,000 $km^2$ in size (Littlewood et al. 1997) and also for ephemeral watersheds in temperate regions (Ye et al. 1997, 1998). Despite the differences in sophistication between the $\Phi$-index method and IHACRES, both use the same basic unit-hydrograph theory and have been employed successfully in deconvolving unit hydrographs based on effective rainfall and direct runoff observations.

## A. Goals and Objectives

The primary goal of this study was to determine whether small watersheds subjected to mine reclamation practices display a stormflow response to rain events that is different from those displayed by similar watersheds that are covered by typical second-growth forests. A secondary goal was to investigate whether intensive surface mining in the Georges Creek watershed of western, Maryland has appreciably altered the stormflow response at the larger river basin scale. Specifically, the following hypothesis was tested.

$H_o$: The mean difference between the stormflow response of a surface mined/reclaimed watershed and a reference watershed is not significantly different from zero.

$H_a$: The mean difference between the stormflow response of a surface mined/reclaimed watershed and a reference watershed is significantly different from zero.

Several objectives were developed to achieve these goals. The first objective was to select a pair of small (<1 km$^2$) watersheds that could be used to conduct a comparison of stormflow characteristics and soil hydraulic properties. The comparison would include measurements of soil infiltration capacities, stream discharge, rainfall runoff ratios, and response lag times. It was desired that watersheds have similar area, slopes, aspects, etc., but differ only in their present LULC. The second objective was to statistically compare the hydrologic response characteristics of each small watershed to a set of storms. The third objective was to investigate the long-term hydrological responses of the larger Georges Creek (186 km$^2$) watershed (extensively surface mined and reclaimed) to the Savage River (127 $km^2$) watershed, which is primarily undeveloped forest. A fourth objective was to test for statistically significant differences in watershed response characteristics between each of the river basins as well as within each river basin over time. This final object was to address the question of whether the hydrological response to rain events within the Georges Creek basin has resulted from a concomitant increase in surface mining and reclamation throughout the watershed.

## Chapter II: METHODS

Five watersheds were used in this study to investigate the hydrological effects of LULC disturbances. The first component of the study involved a characterization and comparison of the hydrologic responses of two small watersheds subjected to different LULC disturbances. The two watersheds would have approximately identical physical features, with the exception that one watershed was surface mined and reclaimed. However, a number of other factors also required consideration in selecting the pair of watersheds including a) proximity to the laboratory and to each other, b) ability to gain landowner permissions and state environmental permits, and c) suitability of sites for stream gaging. A third small watershed was later added for comparisons of annual water balances. The second component of the study involved an historical characterization of hydrologic responses of two larger river basins subjected to different LULC disturbances. The basins were selected on the basis of anecdotal flooding history, proximity to each other, degree of surface mining and reclamation, and availability of historical aerial photos, long-term historical rainfall and streamflow data. After preliminary land use history data were obtained, the larger watersheds were investigated within the following time periods: a) 1950-1966, which represented a period before intensive surface mining and reclamation; b) 1967-1984, which represented a period of early surface mine reclamation; and c) 1985-2000, which represented a period of widespread surface mine reclamation.

### B. Study Sites

In this study I used a Geographic Information Systems (GIS) database to identify watershed physical features (Table 1) for 5 watersheds located in Allegany and Garrett

Counties of western Maryland. For the two small watersheds (MAT1 and NEF1), I delineated watershed boundaries using a Trimble Pro XR Global Positioning System (GPS). The basic approach involved walking the perimeter of each watershed while recording position coordinates at every major change in direction. After collecting coordinates in the field, I differentially corrected the positions using Pathfinder office (v 2.51) and base station data from Morgantown, West Virginia to obtain the highest possible accuracy of watershed area. For two larger basins (Georges Creek and Savage River) I delineated watershed boundaries using topographic maps obtained from the USGS. To calculate watershed slopes, I used a digital elevation model with 30 m resolution generated by the USGS to calculate average slope in ArcView™ 3.1 using the Spatial Analyst™ extension. The software derives the slope of a DEM grid cell using the distance to and elevation of its nearest neighbors. In addition to slope, I calculated drainage densities for the Georges Creek and Savage River watersheds in ArcView™ 3.1 by summing the lengths of all stream segments in the basin and dividing by the total drainage area.

The first watershed (hereafter referred to as MAT1) is a small watershed that has undergone significant surface mining and reclamation (39° 35' 39" N; 78° 53' 29") located in the larger Matthew Run watershed. MAT1 is drained by an ephemeral diversion ditch that is a tributary to Matthew Run (Figure 3). The watershed has a drainage area of 27.1-ha, of which 12.4-ha (46%) has been mined and reclaimed. Mining at MAT1 began in 1982 and reclamation was finished in 1984; reclamation involved returning the land to the approximate original contour and seeding the site with a mix of grasses for hay/pasture (Mining Permit #371, Maryland Bureau of

Mines). Nearly 20 years later the site remains primarily herbaceous vegetation, with several black locust trees (*Robinia pseudoacacia*). Woody vegetation in the forested area of MAT1 watershed has been inventoried by K. Kuers (unpublished data, Department of Forestry and Geology, The University of the South) and summarized by importance value (a combined value for frequency, density, and basal area). The most important species in the forested area at MAT1 are black birch (*Betula lenta*), red maple (*Acer rubra*), and chestnut oak (*Quercus prinus*). Prior to mining, soils were mapped as a combination of Cookport silt loam and a Cookport very stony silt loam (US Soil Conservation Service 1974a). After reclamation, slopes at MAT1 are northwest facing and average 4.5 degrees, with swales and depressions located over much of the area.

A second small watershed (hereafter referred to as NEF1) was selected as a reference site that is characterized as roughly 3.0-ha of contiguous forest (39° 35' 47" N; 78° 54' 29" W) that has never been surface mined, but was selectively timbered nearly 20 years ago (Kuers, unpublished data). NEF1 is located approximately 1.5-km to the west of MAT1. The ephemeral stream draining NEF1 functions as a tributary to Neff Run. Forest cover on NEF1 is generally an unevenly aged deciduous stand consisting primarily of black cherry (*Prunus serotina*), black birch (*Betula lenta*), and sugar maple (*Acer saccharum*). Soils are mapped as Cookport very stony silt loam (US Soil Conservation Service (1974a). Similar to MAT1, slopes at NEF1 are also northwest-facing and average 9.9 degrees.

A third small watershed referred to as the East Branch of Neff Run (EBNR) was added for comparisons of hydrologic budgets. EBNR has a drainage area of 104.2 ha and contains the entire NEF1 site. In contrast to the other two small watersheds (MAT1 and NEF1), EBNR is drained by a perennial stream. Approximately 6 ha (6%) of the watershed has been surface mined and reclaimed, with the remaining 94% forested. Dominant species include black cherry (*Prunus serotina*), red maple (*Acer rubrum*), black birch (*Betula lenta*), and northern red oak (*Quercus rubra*) (Kuers, unpublished data). The average slope of EBNR is 8.0 degrees. Soils are classified as a combination of Cookport very stony silt loam and Buchanan very stony silt loam (US Soil Conservation Service (1974a).

The Georges Creek basin (39° 35' N; 79° 00' W) located in western Maryland (Figure 4) was selected as the river basin that has undergone intensive surface mining and reclamation. Stream discharge for the 187.5 $km^2$ (72.4 $mi^2$) basin has been continuously monitored by a gage at Franklin, Maryland, operated by the United States Geological Survey (USGS) since 1929 (station # 01599000). The soils have been mapped by the US Soil Conservation Service (1974a) as belonging to the Gilpin-Dekalb-Cookport Association. This association is gently sloping to very steep, well drained and moderately well drained. The soils are mostly very stony and are moderately deep over sandstone and shale. The average slope of the watershed is 9.5 degrees (Figure 5).

The Savage River watershed (39° 35' N; 79° 05' W) was selected as a reference site for the larger basin comparison and is located immediately west of Georges Creek watershed (Figure 4). The watershed has a drainage area of 127 $km^2$ (49.1 $mi^2$), slightly smaller than the area gaged in the Georges Creek watershed. The USGS has also been continuously recording stream discharge on Savage River, above the Savage River Dam since 1948 (station # 01596500). In contrast to Georges Creek watershed, 1997 data from the Maryland Office of Planning indicates the watershed is predominantly forested (83%) with some agriculture (15%), development (<2%), and wetlands (<1%) (Hypio 2000). Soils within the Savage River watershed have been mapped as belonging to the Dekalb-Calvin-Gilpin and Calvin-Gilpin Associations (US Soil Conservation Service 1974b). These soils are gently sloping to steep, moderately deep, well-drained and moderately well drained soils. The watershed is slightly steeper than the Georges Creek watershed with an average slope of 12.0 degrees (Figure 5). LULC data for the Savage River watershed are less detailed than those generated in this study for the Georges Creek watershed. Similar to Georges Creek, agricultural land in Garrett County (which completely contains the Savage River watershed) continues to decrease. From 1987 to 1997 alone, the total farmland in Garrett County decreased 11% from over 49,181 ha to 43,582 ha (USDA 2001). Based on data at the county level, LULC in the Savage River watershed has likely remained predominantly forest over the last 50 years with some decrease in agricultural land. Population in Garrett County has exhibited a 28% net increase since 1940, increasing from 21,981 in 1940 to 28,138 in 1990 (Forstall 1995). However, it is unlikely that the Savage River watershed has experienced this rate of growth since there are few population centers in the watershed. As such, development in the watershed over that last 50 years has likely remained at or below 2% of the total watershed area.

C. Field Hydrologic Measurements

Characterizing the hydrological responses of the three small watersheds required a number of primary field hydrologic measurements, while the study of the larger watersheds required acquisition of historical hydrologic data. Hydrologic measurements made at the small watersheds included a) continuous time series of watershed discharge, b) continuous time series of precipitation depths over each watershed, and c) measurements of soil infiltration capacities. Historical hydrologic data for the larger Georges Creek and Savage River watersheds included hourly watershed discharge and rainfall depths measured at two locations within the watersheds.

I installed stream gages in the three small watersheds to provide a continuous record of watershed discharge (Figure 6). Because all work dealing with stream channels in Maryland requires appropriate permits, the Maryland Department of the Environment provided me with permits for the installation of temporary monitoring and research devices (permit #'s 1999965783/99-NT-3220 and 200065922/00-NT-3206). Gages at NEF1 and MAT1 were operational prior to the commencement of the water year on 1 October 1999. Because both of these watersheds lacked natural bedrock controls, I obtained and installed pre-fabricated, pre-calibrated "Montana" flumes (Figure 7) at each site. Each flume (manufactured by Free Flow Inc, Omaha, Nebraska) was constructed of ruggedized 9 mm (3/8 in) thick fiberglass (Figure 7), shipped to Appalachian Laboratory, and transported by truck to each site for installation. Flumes were anchored to 15 cm x 15 cm timbers and wingwalls buried in the streambed and bank. Each flume was equipped with stilling wells that were prefabricated directly onto the flume at the factory. Each gage included a Stevens Type A instantaneous stage recorder equipped with a 15 cm (6 in) diameter painted copper float. Stage recorders were sensitive to water level fluctuations greater than 3 mm (0.12 in).

I chose the appropriate flume dimensions based on the rational runoff method to accommodate runoff produced from rain events with a 10 yr return period. At MAT1, the gage is located in an armored diversion ditch that intercepts surface runoff from the watershed (Figure 3). The flume has a 91 cm (36 in) throat width with a peak capacity of 1.4 $m^3$/sec (Figure 7). At NEF1, the flume has a 30.5 cm (12 in) throat width with a maximum capacity of 0.45 $m^3$/sec (Figure 7). Throughout the study I checked stage records on a bi-monthly basis and returned charts to the lab quarterly. At the lab I digitized the charts showing instantaneous stage heights (obtained from Stevens Type A recorders) and subsequently converted stage heights to hourly discharge and average daily discharge based on the rating curves obtained from Free Flow, Inc. (Table 2).

In all cases I checked stage records for errors and adjusted if necessary before generating discharge measurements. For example, winter months posed a particular problem for data collection since gages were located in remote terrain and could not be heated. At times, stilling wells were subjected to freezing temperatures, which prevented the float from responding to changes in streamflow. Between rain and melt events, the ephemeral streams were dry. On occasions when a rain or melt event was expected, however, stilling wells were thawed using heated water from a campstove to avoid missing a response. Streamflow data were missed at MAT1 for a storm event that occurred on 3 and 4 August 2001 when the pulley on the stage recorder jammed after the cover had been replaced. In addition, data were missed at NEF1 between 1 August 2001 and 30 September 2001 when a rodent derailed the float chain from the stage recorder. In these cases where data missed, I estimated streamflow using the IHACRES software. I only used the modeled data for computation of annual water balances and not in statistical analyses, however.

At EBNR I used a continuously recording stage recorder and a natural channel control (Figure 8) to estimate discharge. The gage was operational on 25 July 2000. The gage consisted of a stilling well set into the stream bank to a depth of 1.5 m. A local metal shop fabricated a stilling well from 24" (ID) steel culvert pipe and a piece of sheet metal that formed the well bottom. The bottom of the well provided for a 15 cm sump below a PVC connection pipe that allowed flow from the stream channel to the well. The pipe was capped and perforated to allow streamwater to enter the well and 'still' to the same elevation as the surface of the stream. A painted copper float with corresponding counterweight was attached to a Stevens Type F chart recorder, which continuously tracked the level of the water in the stilling well. A staff gage mounted to a galvanized metal rod was installed in the stream channel to provide a field check for the chart recorder and serve as a point of reference for stage-discharge calculations. A precision digital water level recorder (model 6541-4) manufactured by Unidata Australia was installed along side the Type F recorder on 28 May 2001 to reduce data post-processing time in the lab.

A stage-discharge relationship was developed for the gage at EBNR. Flow measurements were made 11 times throughout the year at stage heights ranging from

9.2 cm to 22 cm. According to standard procedures, the stream was divided cross-sectionally into cells where cell depth and width were recorded. Mean water velocity of each cell was measured at 0.6 times the water depth using a Marsh-McBirney 'FLOW-MATE' model 2000 portable flowmeter. Instantaneous discharge was then calculated as $Q = A * V$, where Q is discharge in $m^3$/sec, A is the cross-sectional cell area in meters, and V is the average velocity in the cell in m/sec. The rating curve that was used for EBNR between 25 July 2000 and 1 October 2001($r^2$=0.884; n=11, Figure 9) is given in Table 2.

I measured hourly precipitation using two Belfort universal weighing type precipitation gages (model 5-780-300) manufactured by Belfort Instrument Company. One gage was located in a clearing immediately adjacent to the flume at MAT1 ($29^{O}$ 35' 31.5" N, $78^{O}$ 53' 48.9" W) and a second identical gage was located in a clearing near the eastern end of MAT1 (Figure 6). Gages were anchored to wooden platforms located approximately 1 m above the ground surface. Rain gages operated on 8 d hourly charts and were sensitive to precipitation depths greater than 1 mm. During winter months, antifreeze added to the gages prevented freezing and allowed for recording liquid water equivalents (LWE) of snowfall. Unfortunately due to equipment failure, rainfall data collection did not start until 18 December 1999. However, little precipitation occurred during this period. For daily precipitation data lost during the 2 month period I obtained records from a National Weather Service cooperative observing station in Frostburg, MD (located approximately 5 km to the north of the site).

Measurements of soil infiltration capacity were made on each of three randomly located plots on each watershed. The measurements were made by temporarily installing double-ring cylinder infiltrometers (Figure 10) on 12 July 2001 within each of 3 permanent 20 m x 20 m plots established on each watershed (Figure 3). Infiltrometers could not be installed in a strictly random manner on the plots, since the instruments required sites that were relatively level and stone free. Infiltrometers were constructed of 16 ga. sheet metal formed into an outer and inner ring. The water supply reservoir was constructed from a 45 cm length of cylindrical PVC pipe (30 cm I.D.). Each end was capped using 0.03 cm thick plexi-glass. The bottom end of the reservoir contained two short sections of 1.3 cm PVC pipe. One pipe extended out of the reservoir 2 cm more than the other allowing for water to fill the infiltrometer. The shorter pipe allowed air into the reservoir and kept the water at a constant depth in the infiltrometer. The reservoir was also equipped with a graduated tube (modified from a laboratory burette) to monitor declines in water level in the reservoir and provide a direct measurement of water entry to the soil over time. Water in the outer ring was maintained at the same level as the inner ring to avoid effects of differential head pressures. Infiltration capacity (mm/min) was determined as the rate at which water was added to maintain a constant water level in the center ring of the infiltrometer. For the purpose of this study and based on the relatively homogeneous soils, it was assumed that the sampling design yielded estimates that are representative of the entire watershed.

## D. Historical Hydrologic Measurements

Hydrological characterization of the George's Creek and Savage River watersheds over the long-term was accomplished utilizing various data obtained from the USGS and the

National Climatic Data Center (NCDC). Data needs includes the following long-term records: a) daily precipitation depths at Frostburg and Savage River Dam from 1948 to present; b) hourly precipitation records for Savage River Dam 1948 to present; and c) hourly streamflow at Georges Creek (1929 to present) and at Savage River Dam (1948 to present). Each of these data sets, with the exception of the mining history, has been quality checked and is available from the USGS and NCDC.

Rain events were selected for intensive characterization of watershed responses. The fifteen most intense storms (daily resolution) were included if they met the following criteria: a) events occurred between May and October; b) the events were of relatively uniform intensity over the entire watershed; c) and the events were relatively isolated from other storms. Storms were required to be of uniform intensity over the watersheds for unit hydrograph analysis. Events were considered uniform over both watersheds if daily precipitation measured by the stations at the northern and southern ends of the watershed differed by less than 20%. At the northern end of the watershed, a National Weather Service cooperative observing station at Frostburg has recorded historical daily precipitation for more than 50 years. At the southern end, the USGS station at Savage River Dam has recorded hourly precipitation for 54 years. Storms were also required to be isolated to eliminate multiple hydrograph peaks and dampen the effects of antecedent moisture conditions that can affect runoff generation from storm to storm. Rain events were considered isolated if no precipitation occurred within an arbitrarily chosen three days before or after a specific event. The hourly data from the USGS station at the Savage River Dam were ultimately used to estimate areal rainfall over each of the two larger basins.

Historical stream discharge records for Georges Creek and Savage River were obtained from the USGS for each of the selected rainstorms. It was necessary to reconstruct hourly discharge values from historical stage "strip" charts and stage-discharge relationships, since hourly stream discharge data were not archived digitally. Stage and stage-discharge data were obtained from archives at the USGS field office in LaVale, Maryland, with the exception of records dated prior to 1965 that were requested from the national archives located in Washington, DC. Records were then delivered to the LaVale USGS field office where the stage records for selected storms were photocopied. Stage records were then digitized and converted to hourly stage values at the Appalachian Laboratory using "MDFLOW", a software program developed by K.N. Eshleman (personal communication). Based on historical rating curves reconstructed from rating tables, hourly stage values were then converted to instantaneous discharge.

E. Unit Hydrograph Deconvolution

Several unit hydrographs for the small watersheds were deconvolved using both the Φ-index method (Chow, et al. 1988) and IHACRES. Each of the models was based on basic unit hydrograph theory, although IHACRES uses a more sophisticated mathematical approach. However, satisfactory model fits could not be obtained when IHACRES was used to generate unit hydrographs for historical rainfall-runoff data from the larger Georges Creek and Savage River watersheds.

The Φ-index method was used for deconvolving unit hydrographs for the small watersheds for a thunderstorm that occurred on 6 August 2000 (this storm caused low-lying areas in the Georges Creek to be flooded). Based on the Φ-index approach, unit hydrographs were deconvolved assuming a constant rate of rainfall abstraction. Values for $\Phi$ were calculated via trial and error by subtracting a value ($\Phi$) from the rainfall pulses that were believed to have contributed to direct runoff until a value for $\Phi$ yielded an effective rainfall hyetograph that, when integrated, was equal to the area under the direct runoff hydrograph.

Because of the sophistication of IHACRES, the software was used to unit hydrographs from June to October for water years ending 2000 (year 1) and 2001(year 2). These months were chosen based on the constraints of the model that allowed for best model fit. The primary constraints of the model required that a) the subperiod of record started and ended at times when flow was at or near zero, and b) the subperiod of record contained no snowfall events (typically November to April in western MD). The basic modeling approach involved a non-linear component in the model that used a watershed wetness index that varied from zero to unity depending on the time since last rain. Effective rainfall (or the rainfall that was exported from the watershed as streamflow) was then modeled over a defined time step as a percentage (ranging from 0-100%) of the watershed wetness index. The second component assumed a linear relationship between effective rainfall and flow (streamflow subsequently decays exponentially following a unit impulse of effective rainfall). Unit hydrograph theory is then used to estimate total streamflow over the user-defined sub-period.

F. Historical Land Use / Land Cover Derivation

Historical LULC for the Georges Creek basin was derived for several time periods based on historical aerial photographs. Aerial photographs beginning with 1938 were obtained from the United States Department of Agriculture (Ben Cooper, Allegany County Soil Conservation District, Cumberland, MD). Certain years of photographs were used to provide detailed resolution of LULC change over the time periods used in this study: a) 1938, pre-surface mining; b) 1962 and 1982, pre to early surface mine reclamation; and c) 1997, widespread surface mine reclamation. Due to time limitations and labor intensity, LULC data for Savage River basin were obtained from the Maryland Department of Planning (http://www.mdp.state.md.us) other historical data were obtained from the U.S. Census Bureau (http://www.census.gov) and the U.S. Department of Agriculture (USDA 2001) .

Aerial photographs for Georges Creek required georeferencing before LULC classes could be digitized from the photos. Approximately 120 photographs were scanned with a UMAX Mirage II scanner at 600 dpi and were archived on CD-ROMs. Images were georeferenced using the Imagewarp extension in Arcview™ GIS v.3.1. In general, Imagewarp references photos using ground control points (a minimum of 10 in this study) and warps images using cubic convolution on a $4^{th}$ order polynomial. Photographs were georeferenced to control points selected on USGS orthorectified digital topographic quadrangles.

LULC was classified into nine dominant classes (Appendix II). These classes were based on the Multi-Resolution Land Characteristics Consortium (MRLC) classification scheme used by the U.S. Environmental Protection Agency (USEPA) (http://www.epa.gov/mrlc/). Appendix II lists each of the classes and criteria used during on-screen digitizing in Arcview™ GIS v3.1.

## G. Data Analysis

Annual water balances for each watershed were based on a mass balance approach. Annual evapotranspiration was calculated as the residual of areal precipitation inputs and annual watershed runoff. Calculation of evapotranspiration by difference is a standard approach in hydrological studies where actual evapotranspiration cannot be readily measured (Dunne and Leopold 1978). The effects of changes in soil storage were assumed to be negligible based on the approach used by the USGS (Dunne and Leopold 1978). Annual water balances were calculated on a water year basis beginning on 1 October and ending on 30 September of the following year.

Watershed response characteristics for each watershed were analyzed for differences both between watersheds on a storm by storm basis, as well as for changes over time from the onset of surface mine reclamation. Storm hydrographs were separated into baseflow and stormflow based on the separation method detailed in Dunne and Leopold (1978) (Figure 10-4 [b]). A paired t-test was used to test the hypothesis that the mean difference in watershed responses between the two watersheds is not significantly different from zero. Changes in hydrological response characteristics for each basin over time were tested using simple linear regression with storm date as the independent variable (1950 to 2000).

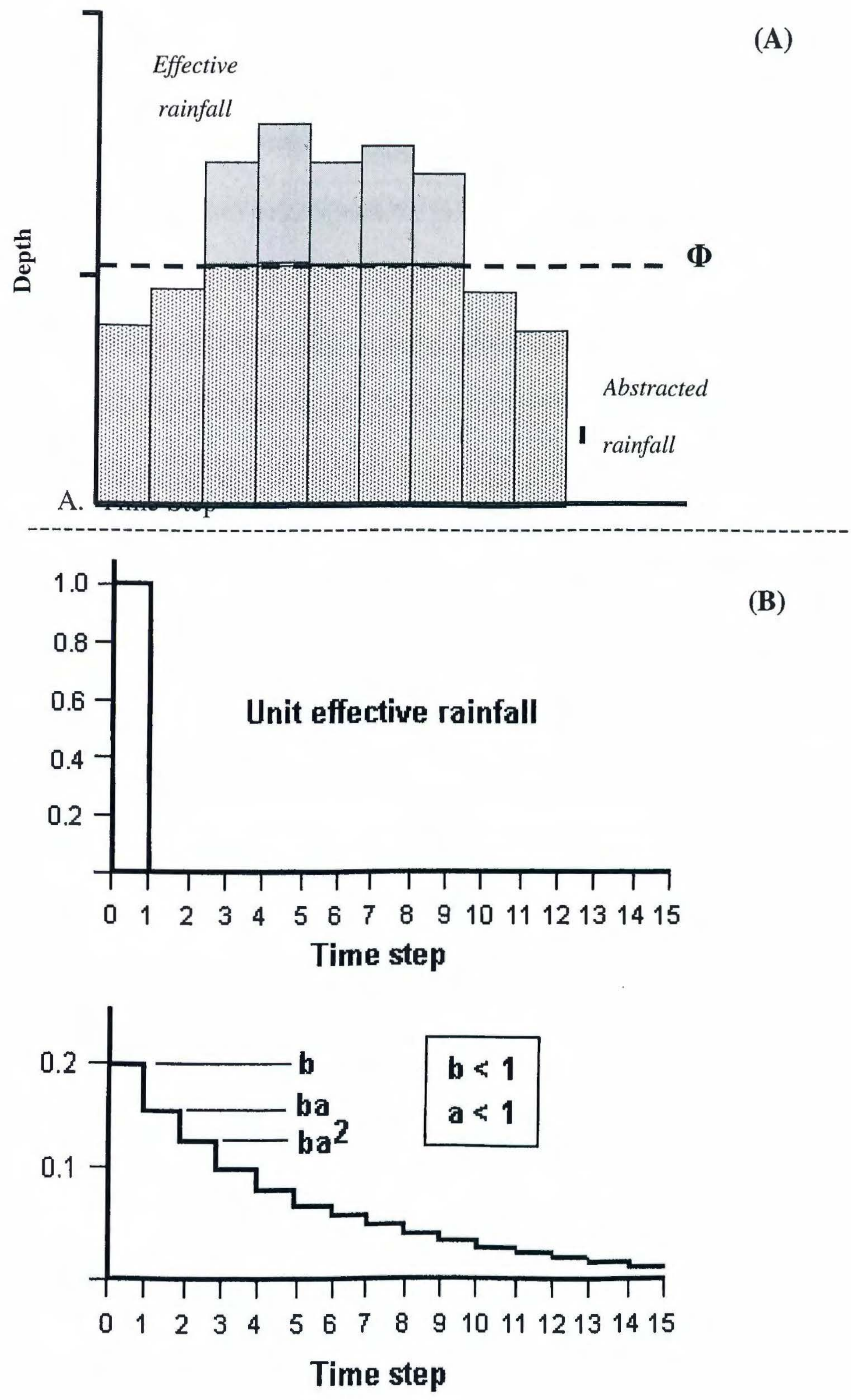



Figure 1. Generalized model of constant rate of abstraction used in the Φ-index method (A) and non-linear decay used in IHACRES (B, from Littlewood et al. 1997).

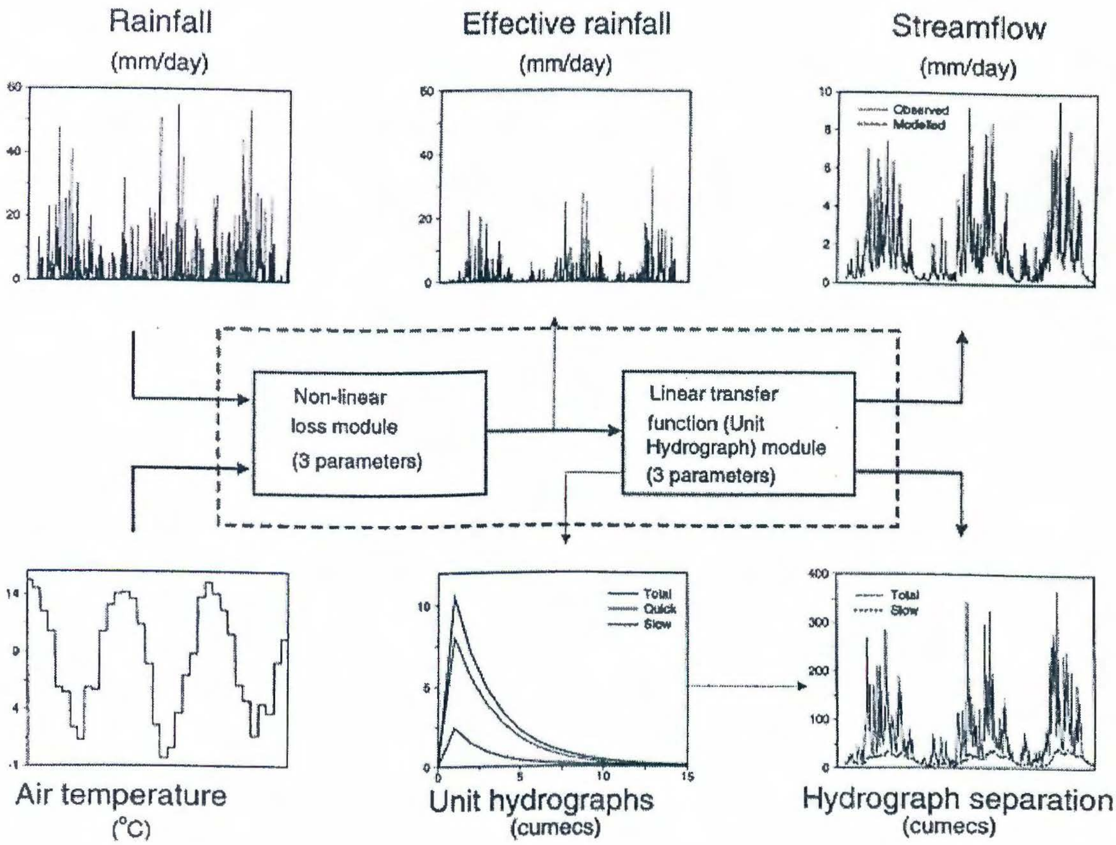



Figure 2. Schematic representation of IHACRES used to deconvolve unit hydrographs at MAT1 and NEF1 adapted from Littlewood et al. (1997).

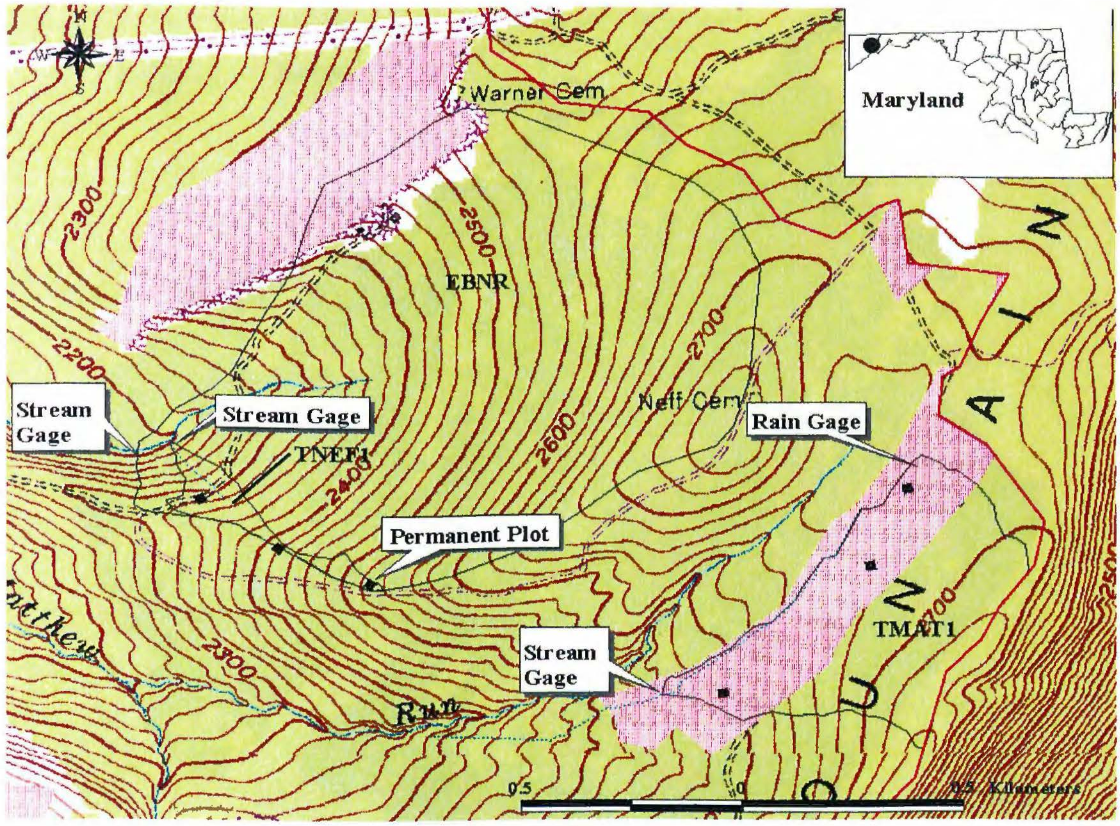



Figure 3. Locations of stream gages, watershed boundaries, permanent plots, and surface mined area (shaded) for the small watershed study located on Dans Mountain, Allegany County, Maryland.

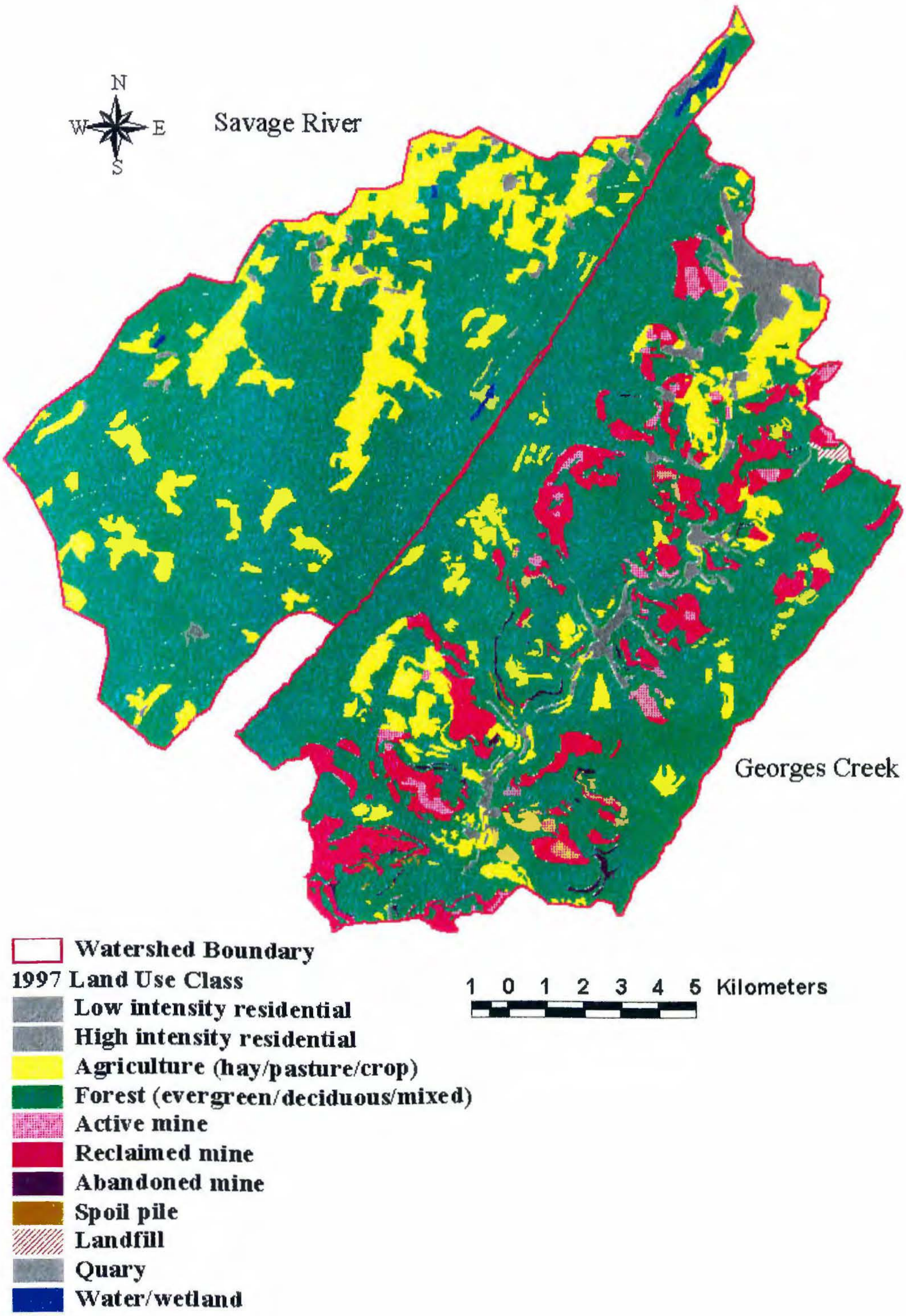



Figure 4. Locations, watershed boundaries, and 1997 LULC for the Georges Creek and Savage River watersheds, Allegany and Garrett Counties of western Maryland.

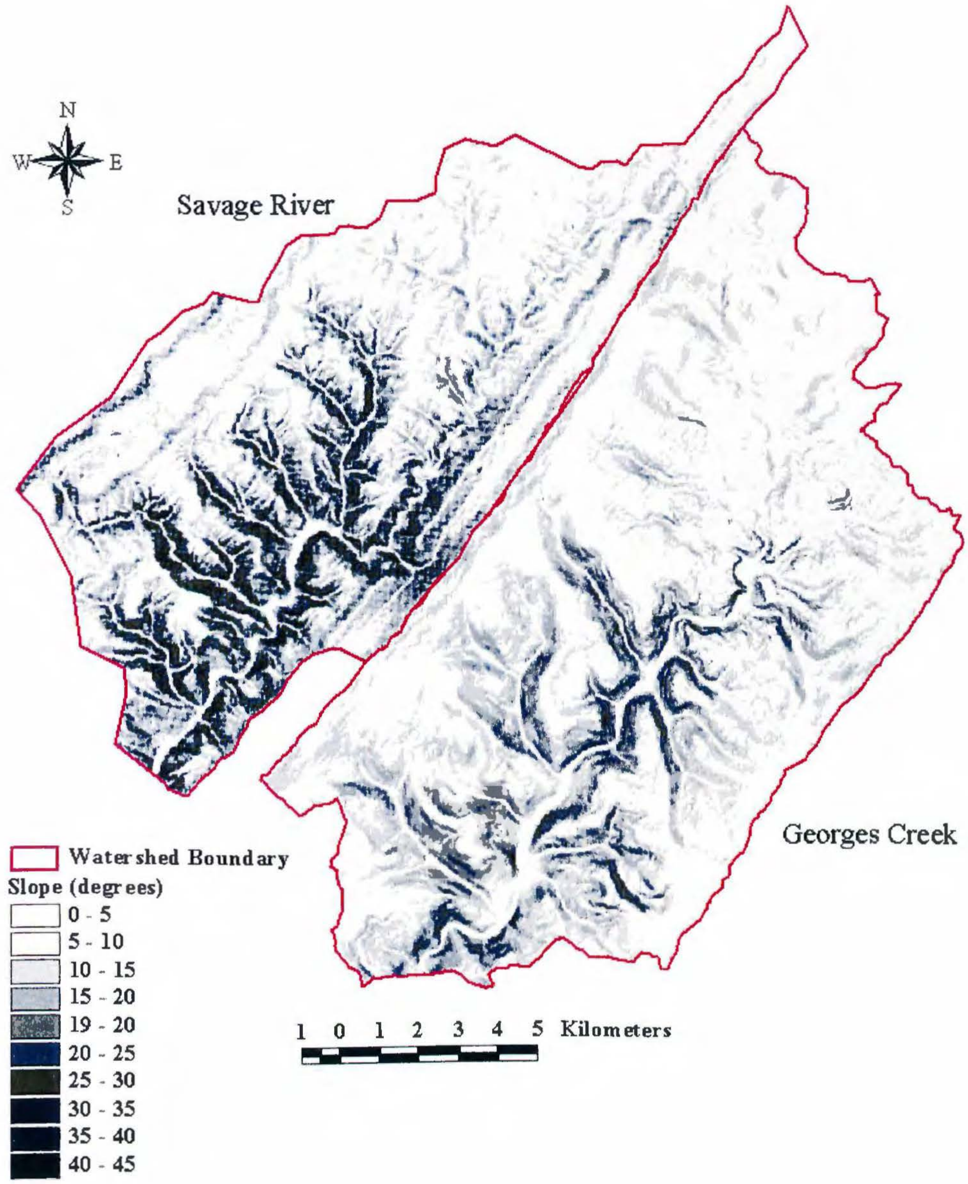



Figure 5. Slope map of Georges Creek and Savage River watersheds, Allegany and Garrett Counties.


Figure 6. Equipment installed at MAT1 for gaging watershed hydrologic inputs and outputs. Stream gage (Montana flume) is similar to that installed at NEF1.

| Throat width | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 36 | 88-3/4 | 36 | 61-7/8 | 27 | 18 | 17 |
| 12 | 76-7/8 | 36 | 33-1/4 | 27 | 18 | 17 |

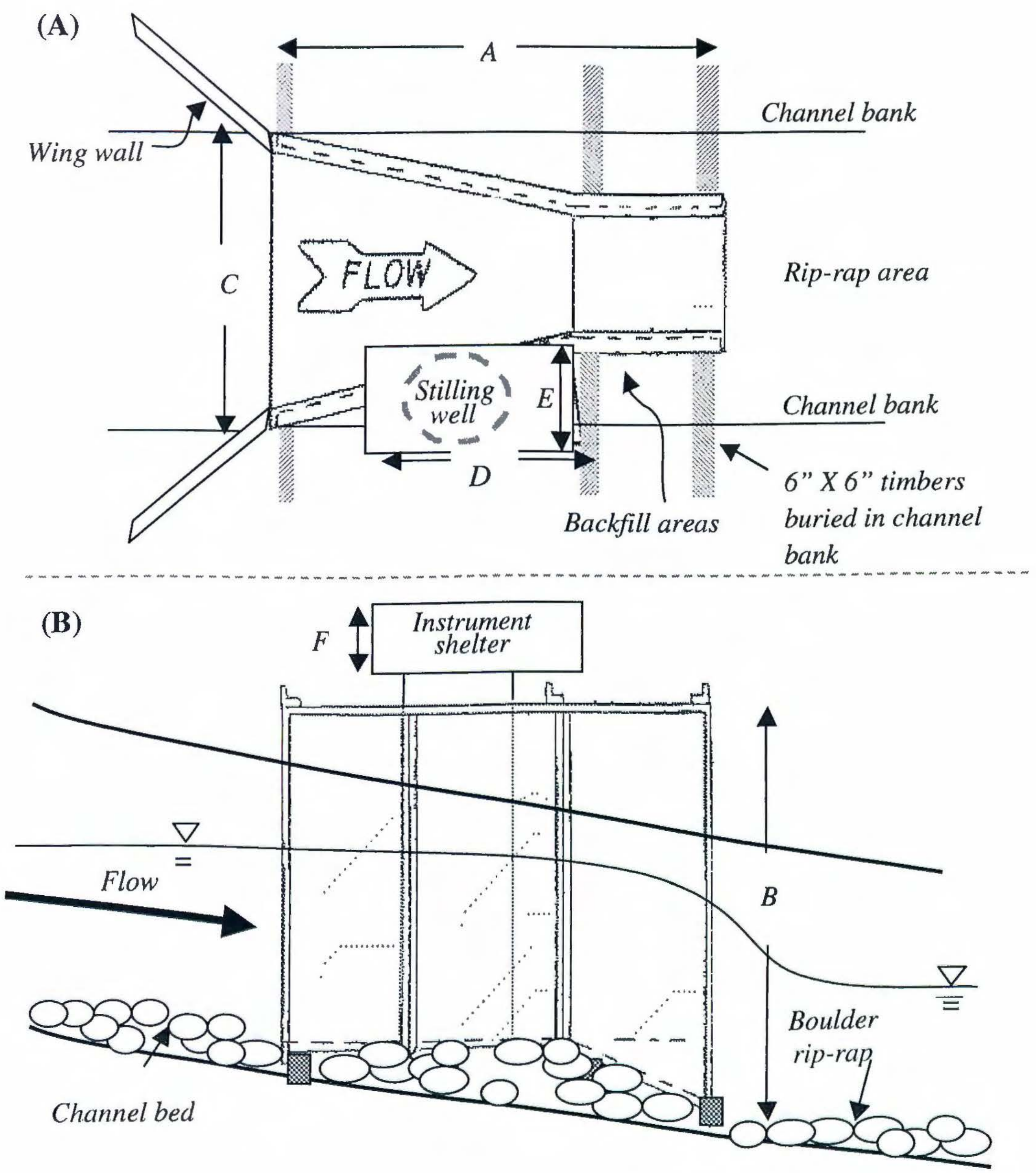



Figure 7. Plan view (A) and side view (B) of Montana flumes installed at the MAT1 and NEF1 watersheds (dimensions in inches shown in accompanying table).

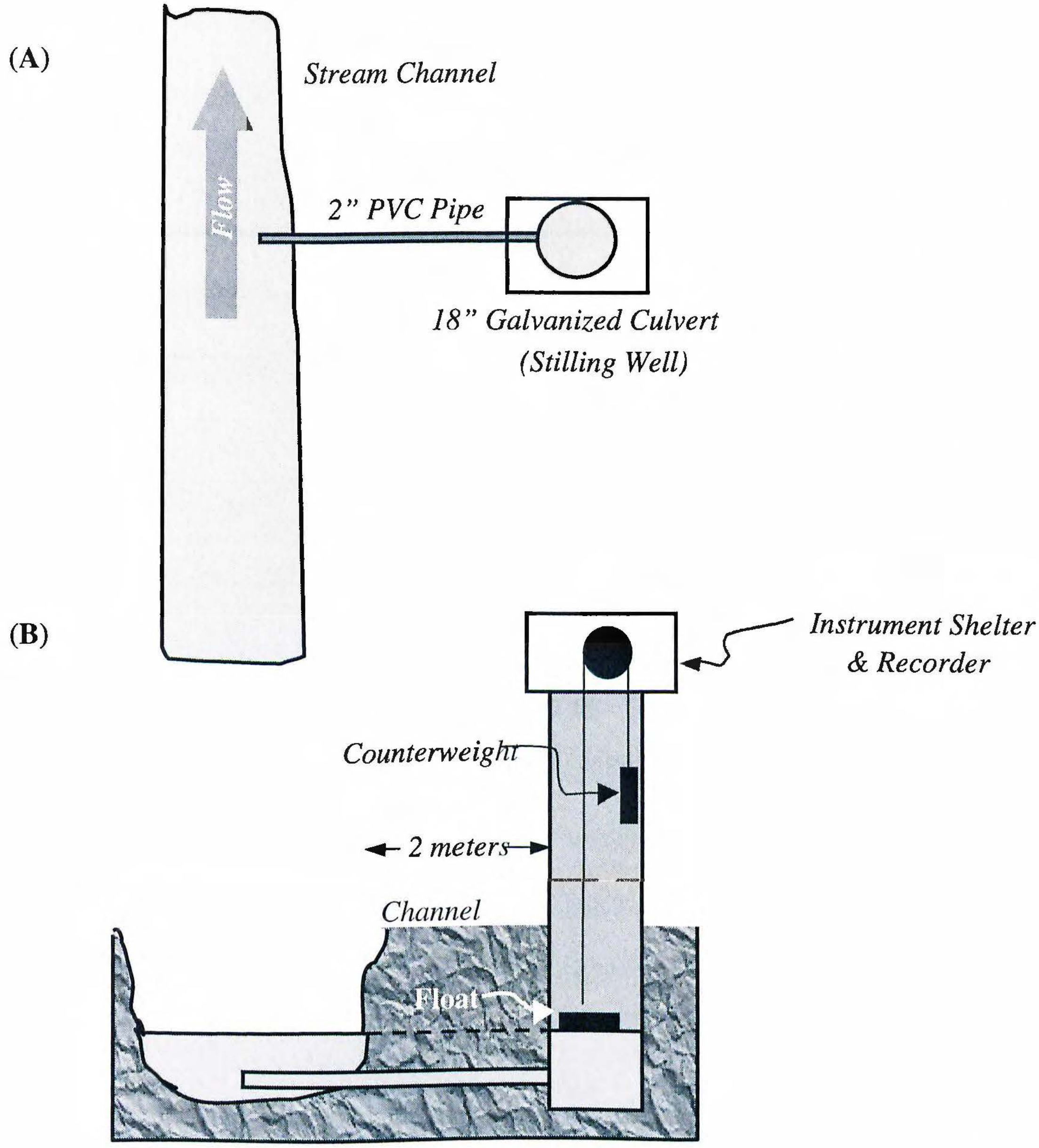



Figure 8. Plan view (A) and side views (B) of stilling stream gage installed on the East Branch of Neff Run (EBNR) located on Dans Mountain, Allegany County, Maryland.

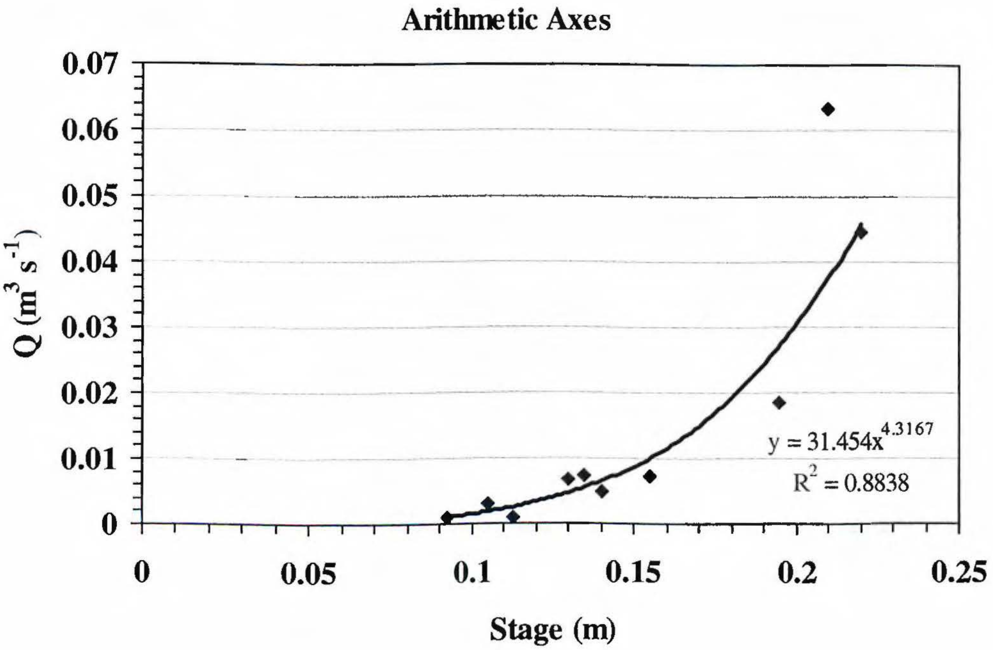
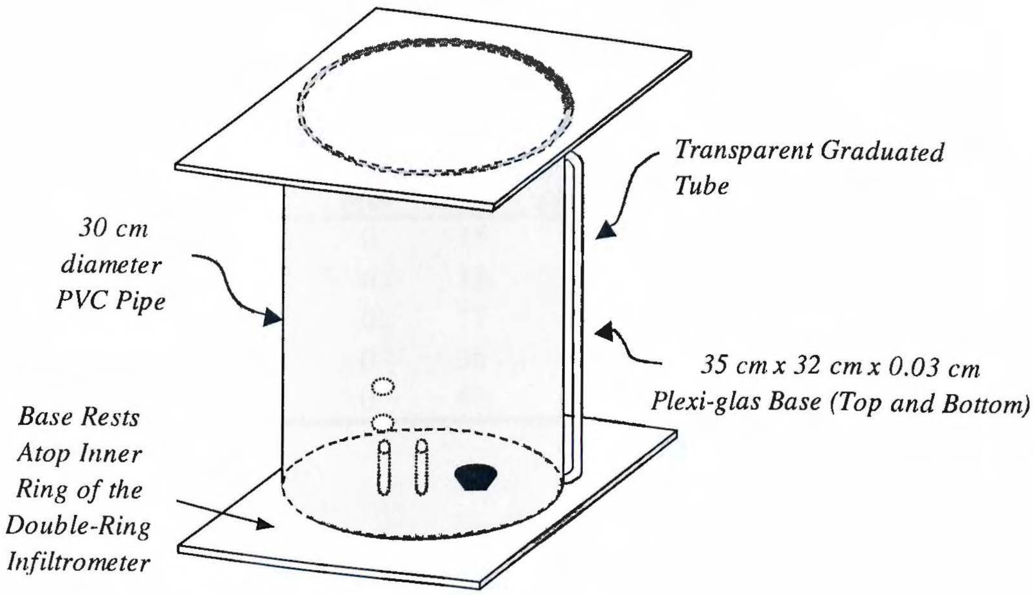
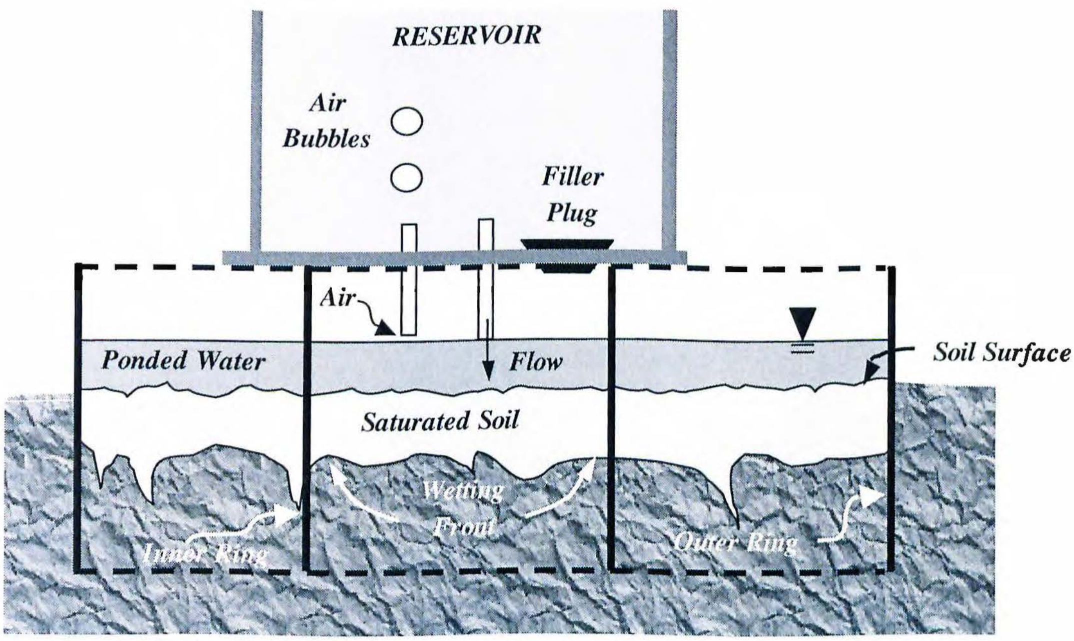



Figure 9. Stage-discharge relationship for the gage installed on the East Branch of Neff Run (EBNR) during the period from 25 July 2000 to 1 October 2001.




***Reservoir for double-ring infiltrometer***




***Flow regulator for double-ring infiltrometer***

Figure 10. Schematic of double-ring infiltrometer and water reservoir used to measure infiltration capacity (adapted from Eshleman 1985)

Table 1. Drainage area, slope, and elevation of watersheds used in comparative analysis.

| | Area ($km^2$) | Slope (degrees) | | | Elevation (meters AMS) | | |
|---|---|---|---|---|---|---|---|
| | | *Min* | *Max* | *Mean* | *Min* | *Max* | *Mean* |
| MAT1 | 0.27 | 0 | 15 | **5** | 783 | 851 | **825** |
| NEF1 | 0.03 | 6 | 13 | **10** | 689 | 778 | **727** |
| EBNR | 1.0 | 0 | 17 | **8** | 679 | 849 | **771** |
| GCRK | 186 | 0 | 36 | **10** | 302 | 911 | **658** |
| SRIV | 127 | 0 | 43 | **12** | 459 | 920 | **746** |

Table 2. Stage discharge relationships for the stream gages installed in the small catchment study.

| # | Watershed | Throat Width (in) | Rating Curve |
|---|---|---|---|
| 1. | MAT1 | 36 | $Q_{(cfs)}= 12\ H_a^{\ 1.5661}$ |
| 2. | NEF1 | 12 | $Q_{(cfs)}= 4W\ H_a^{\ (1.522\ W\ ^\wedge\ 0.026)}$ |
| 3. | EBNR | N/A | $Q_{(cms)}=31.45\ [H]^{4.3167}$ |

Q = discharge, $H_a$ = head (depth) in feet, H = stage (height) in meters, W = flume throat width in feet.

## Chapter III: RESULTS

This study found a number of significant differences in the hydrological responses of watersheds subjected to LULC, specifically when comparing the surface mined and reclaimed watershed to one that was entirely forested. The small watersheds (MAT1 and NEF1) responded similarly on a water year basis, but varied in their response to individual rain events. Storms at MAT1 produced significantly greater runoff ratios, total runoff, and peak runoff than at NEF1. Lag times for the two small watersheds were similar for the events analyzed in this study. However, at the river basin scale (Georges Creek and Savage River), watersheds varied from each other primarily in the timing of response to rainfall events. Despite widespread LULC change, other hydrological response characteristics (runoff ratios, peak runoff, total runoff) exhibited little difference at the river basin scale when compared between the two basins or within the basins over time.

Annual hydrographs for water years 1 (2000) and 2 (2001) at MAT1 and NEF1 can be found in Figure 11. Hydrographs for the two water years of streamflow indicate that MAT1 tends to produce higher, narrower peaks than NEF1. For the majority of the water year, both watersheds responded primarily to major rain events and snow melts and produced little to no baseflow between rain events. However, during wetter months (e.g., April and May) NEF1 produced some sustained baseflow between storms.

Annual water balances (1 October to 30 September) for all sites as well as the normal year for Georges Creek and Savage River are shown in Figure 13. On an annual basis, each of the watersheds produced similar runoff yields, although MAT 1 tended to produce more total runoff than NEF1. Over the two years, roughly 26% of the rainfall input to the MAT1 watershed leaves as surface runoff, compared to 25% at the NEF1 watershed. Runoff yields varied slightly between years 1 and 2. MAT1 produced similar annual runoff in both years, while NEF1 decreased by 15%. Interestingly, this decrease at NEF1 occurred despite an increase of 139 mm of precipitation in year 2 making it a wetter than normal year (Figure 12). Compared to long-term records for Georges Creek and Savage River, these estimates of annual yield are close to normal values (Figure 13) although the 2001 water year tended to be somewhat wetter than normal. ET yields were slightly higher at the small watersheds for both of the water years and also higher than the long-term averages. Long-term annual runoff yields for Georges Creek tend to be 100 mm less than the long-term average for Savage River Watershed.

Statistically significant differences were observed between runoff coefficients and total event runoff produced at MAT1 and NEF1. Mean runoff coefficients for were calculated for the eight largest storms for which data exist at both gages (Figure 14). Runoff coefficients were significantly higher at MAT1 than at NEF1 ($p \leq 0.03$), on average by as much as 2.5 times (Figure 15). Runoff coefficients at MAT1 averaged 0.11 ranging from less than 0.01 to 0.26 (s.e. = 0.013) compared to NEF1 where runoff coefficients averaged 0.04 ranging from no response to 0.13 (s.e. = 0.007). Runoff coefficients did not correlate with maximum rainfall intensity or total event rainfall ($p \leq 0.05$). The mean difference in total runoff (MAT1 – NEF1) for the eight largest storms where data exist for both gages was significantly greater than zero based on a one-tailed t-test. ($p \leq 0.05$). MAT1 yielded roughly three times more total event flow than NEF1

(Figure 16). Total event runoff at MAT1 averaged 5.0 mm per event and ranged from no response to 14 mm. Response at NEF1 was significantly lower averaging 1.7 mm per event ranging from no response to 5.1 mm. This trend of greater total runoff at MAT1 was observed in all but one of the storms, which occurred on 31 July 2000 (Figure 17). Total runoff at MAT1 was significantly correlated to total event rainfall ($r= 0.794$; $p \leq 0.01$; s.e. = 3.1; n=10). Total rainfall explained 63% of the variation in runoff at MAT1. At NEF1 however, total rainfall explained less than 21% of the variation in total runoff and a statistically significant relationship ($r = 0.455$; $p \leq 0.05$; s.e. = 1.8; n = 8) was not observed.

Peak runoff rates for the eight storms investigated at MAT1 were on average twice as large as those found for NEF1, although the mean difference between the two watersheds was not significantly different from zero at the 0.05 level. Peak runoff rates at MAT1 were consistently higher than at NEF1, with the exception of one storm on 31 July 2001 (Figure 18). MAT1 averaged 1.0 mm/h (S.E. = 0.18) ranging from less than 0.1 mm/h response to 3.6 mm/h. On one occasion, peak runoff rates at MAT1 reached 5.9 mm/h. Peak runoff rates at NEF1 were lower, averaging 0.5 mm/h (s.e.= 0.09) and ranging from no response to 1.6 mm/h. Peak runoff rates at MAT1 were significantly correlated with maximum rainfall intensity ($r = 0.670$; $p \leq 0.05$; S.E.= 1.5; n= 10), and a linear regression model explained 45% of the variation in peak stormflow (Figure 19). In comparison, peak runoff rates at NEF1 were not significantly correlated with maximum rainfall intensities ($r = 0.543$; $p \leq 0.05$; s.e.= 0.6; n=8), and a regression model only 30% of the total variation in peak stormflow.

Timing of runoff response at NEF1 and MAT1 was also calculated to compare the responsiveness of the watersheds to the accumulation of the rainfall pulses. For the eight storms compared in this study, the mean centroid lags (center of rainfall mass to center of runoff) based on hourly rainfall and runoff data for each watershed averaged 3 h, indicating no significant difference in the timing of response to rainfall.

Two-hour unit hydrographs were deconvolved from rainfall and runoff observations for a thunderstorm occurring on 6 August 2000 using the $\Phi$-index method (Figure 20A). IHACRES was also used to deconvolve 1-hr unit hydrographs for the growing season (June to October) for both years 1 and 2 (Figure 20B). For the thunderstorm event, unit hydrograph shapes for each watershed were strikingly similar. MAT1 peaked slightly higher and receded more steeply than NEF1. Similar results were obtained using IHACRES (see Appendix III for model fit parameters) when unit hydrographs were developed over the entire growing season. Similar to the 2-hr unitgraph for 6 August 2000, hydrographs peaked slightly higher at MAT1 than at NEF1. Little change in unit hydrograph response was observed between year 1 and year 2. Unit hydrographs for both watersheds peaked approximately 0.1 mm higher in year 1 than in year 2.

Soil infiltration capacity (or maximum infiltration rate assuming ponded water conditions) was also measured as an important variable influencing watershed stormflow response. As expected, steady-state infiltration capacities were lower at the reclaimed surface mine plots than on the forested reference watershed plots. This can be readily seen when examining the cumulative depth of water infiltrated at each plot (Figure 21). The point at which the curves become nearly linear provides an estimate of the steady-state infiltration capacity of the soil. The reclaimed area at MAT1 exhibited steady-state infiltration rates less than 1 cm/hr (n=3), or rates below the detection level of the infiltrometer. In contrast, soil infiltration experiments at NEF1 yielded infiltration capacities that averaged nearly 30 cm/hr (n=2). For the 10 most intense storms at MAT1 and NEF1, soil infiltration capacities were exceeded in every case at MAT1 (Figure 21). However, at NEF1 soil infiltration capacity was never exceeded by maximum hourly rainfall intensities.

In addition to intensive measurements made for the two small watersheds, the physical and hydrological characteristics of Georges Creek and Savage River basins were also determined. During the last 60 years, the Georges Creek basin has undergone a wide range of LULC changes. Most change has occurred primarily within four LULC classes: surface mining, agriculture, forest, and development (Figure 23). Although some of these categories (e.g., forests) have experienced minimal net change, others like agriculture and mining have undergone significant changes (Figure 24). Of most importance to this study are those LULC changes that have a direct effect on stream hydrology, such as those that alter evapotranspiration and imperviousness. LULC change statistics in the Georges Creek watershed for each time period are given in Table 3.

Surface mining and reclamation in the Georges Creek watershed was one of the most visible and potentially the most influential factor on hydrology in the watershed (Figure 25A). Before the enactment of SMCRA in 1977, a limited number of surface mined lands underwent reclamation with a peak in surface mining and reclamation occurring in the 1980's (John Carney, MD Bureau of Mines, personal communication). According to results obtained in this study, by 1982, 8.8% (1,649 ha) of the watershed had been surface mined and reclaimed. Total reclaimed area in the watershed has continued to increase such that by 1997 13% (2400 ha) of the watershed is reclaimed minesoils. Most of this land conversion came from two sources: agricultural lands and forestlands that were mined and reclaimed. In 1997, nearly 26 of the 105 mines in the watershed were within 50 m from surface waters, making stream channels highly susceptible to runoff produced from these adjacent mine lands.

Active mining operations began in the late 1940's and peaked by the 1980's (Figure 25B). In 1962, active mining represented less than 1% of LULC in the watershed. Only 20 years later, active mining operations had increased by 700%. Available aerial photos show that surface mining peaked in 1982 with approximately 53 mines in active operation, representing nearly 3.5% of the total watershed LULC. Between 1938 and 1982, active surface mines were primarily located on lands that were previously agricultural land or had been forested. In 1997, most active mines were either previously forested, or were mines that were still in operation from 1962 or had been abandoned and re-mined (Figure 25C).

Agricultural lands were one of several land uses that declined over the 60 yr period (Figure 25D). In 1938, 32% of the watershed was pastured, cropped, or planted as hayland. Over the next several decades, agricultural lands steadily declined. By 1997, less than 10% of the watershed was in active agriculture. Agricultural lands were primarily lost to surface mining or had been abandoned to re-generate as forestland.

Overall change in forested areas remained relatively low over the study period (Figure 25E). Nearly 65% of the Georges Creek watershed was covered in forests in 1938. Some forest regrowth occurred between 1938 and 1962 (74%), but was followed by a slight decrease through 1997 (70%). Most forest regrowth occurred on abandoned agricultural lands. However, losses to surface mining and development offset any increases resulting in a net decrease in forest area. In 1997, a small area of strip mined land (4% of all forest lands) had returned to forest after mining.

Overall development in Georges Creek on a per area basis, both commercial and residential, changed slightly from 1938 – 1997 (Figure 25F). The basin underwent a net increase in development of 2.2% (2.4 – 4.6). However, this represented approximately a doubling of developed area. Most of the change occurred in the low intensity residential category, which rose from 0.6 to 2.5%.

The area of wetlands in the Georges Creek basin was found to be negligible. According to the National Wetlands Inventory (NWI), wetlands cover less than 1% of the basin.

Little difference was observed in response characteristics on a storm-by-storm basis for 15 storms analyzed the Georges Creek and Savage River basin study. The primary difference in watershed response between the two basins was in the mean centroid lag. Georges Creek tended to respond on average three hours more quickly than Savage River (Figure 26). Mean runoff ratios for Georges Creek were significantly correlated to runoff ratios calculated for Savage River (Figure 27) ($p \leq 0.001$, $r^2 = 0.99$, s.e. = 0.0139, n = 15). In addition the slope of the regression line was not significantly different from 1 nor was the intercept significantly different from zero ($p < 0.05$). No significant difference ($p \leq 0.05$) was observed in the mean peak runoff or runoff ratios for the Georges Creek and Savage River basins, even though Georges Creek often (73% of the time) produced higher peak runoff than the Savage River. Mean runoff ratios were essentially identical (GC = 0.068; SR = 0.075). In addition, there was no significant trend in runoff ratio, peak runoff, total runoff, or centroid lag when examined for each watershed over time ($p \leq 0.05$, $n = 15$).

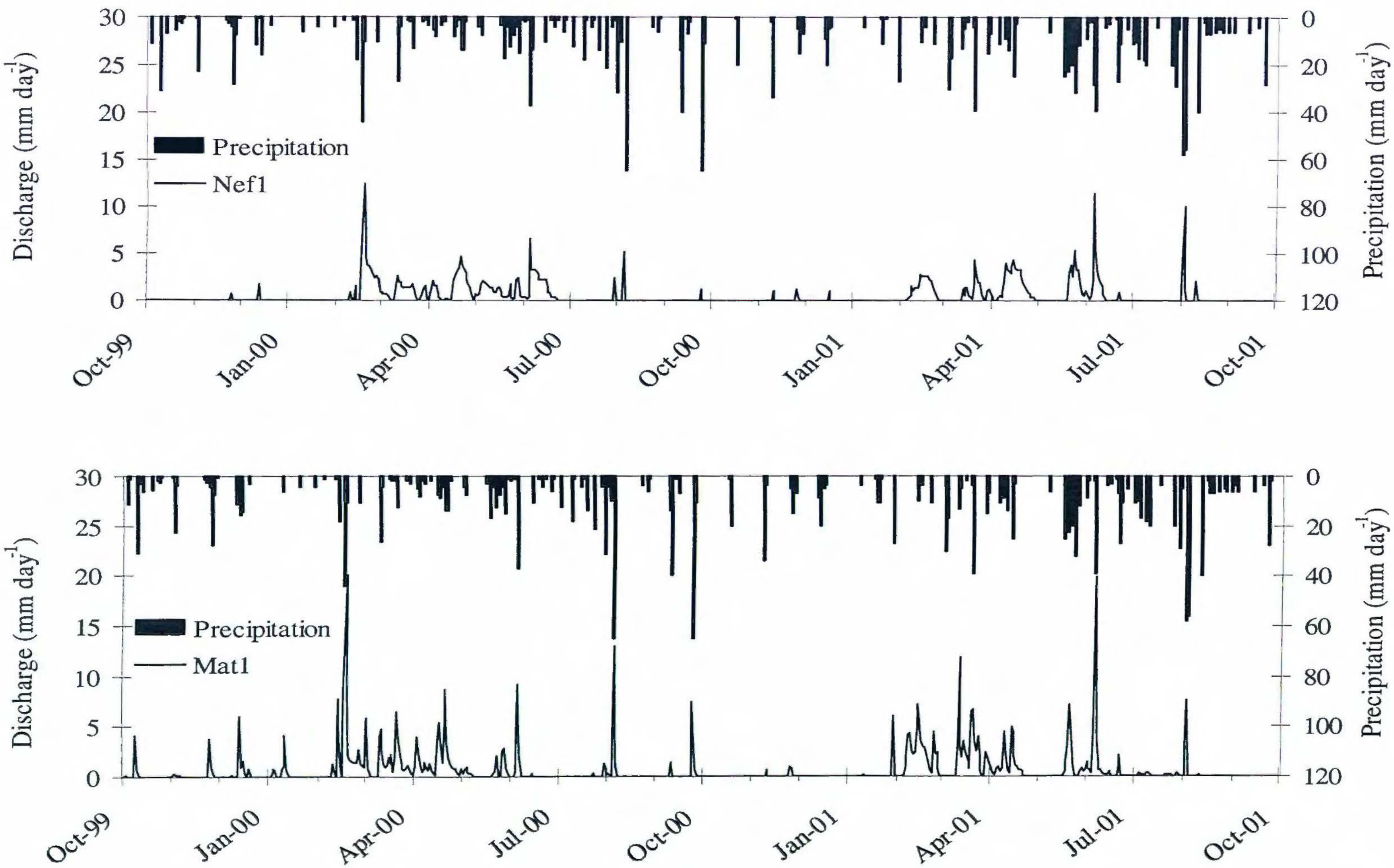



Figure 11. Average annual discharge (normalized by area) and daily precipitation at MAT1 and NEF1 from 1 October to 30 September 2001.

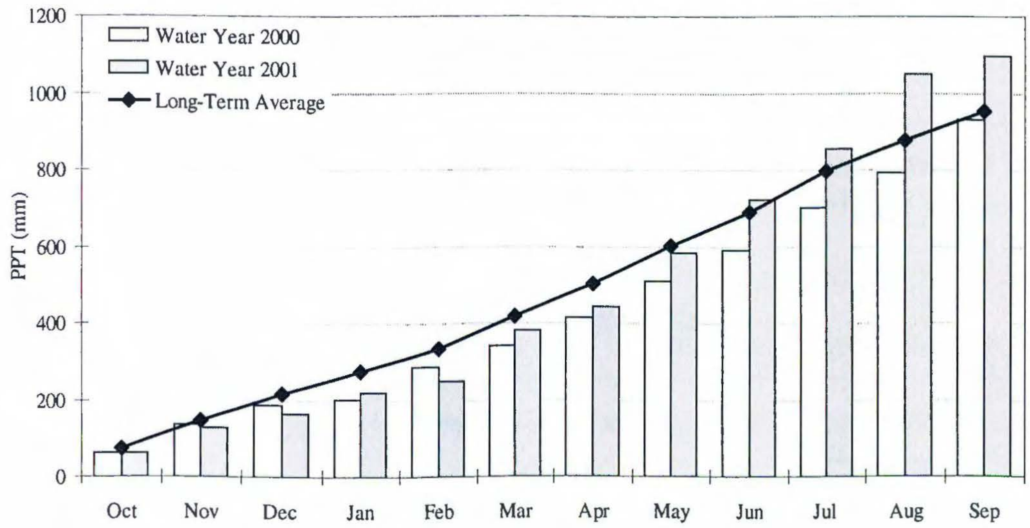



Figure 12. Long-term average (1961-1990) cumulative precipitation observed at Savage River Dam station, Garret County, Maryland by water year.

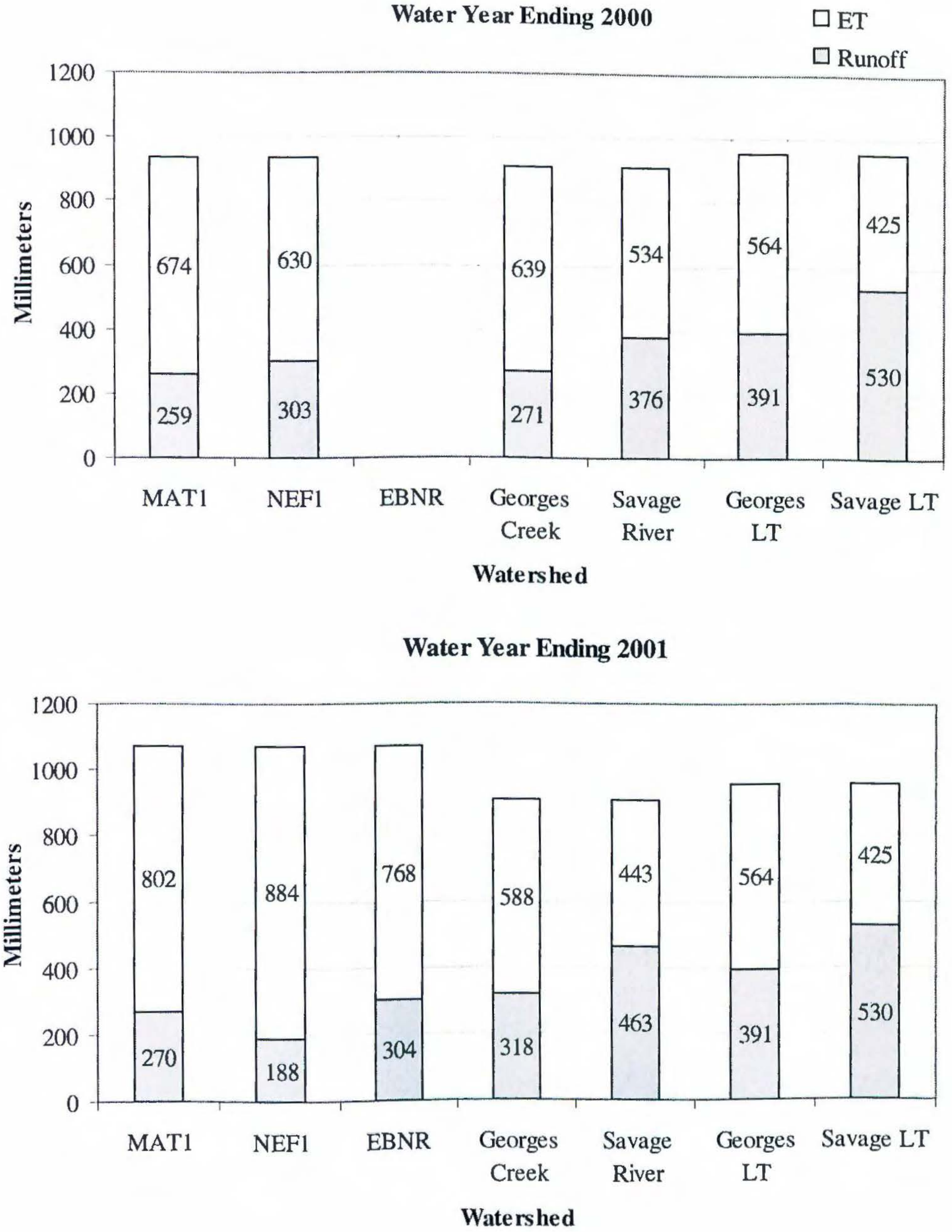



Figure 13. Annual water balances for the small watersheds and larger basins for water years ending 2000 and 2001 and long-term (LT) averages.

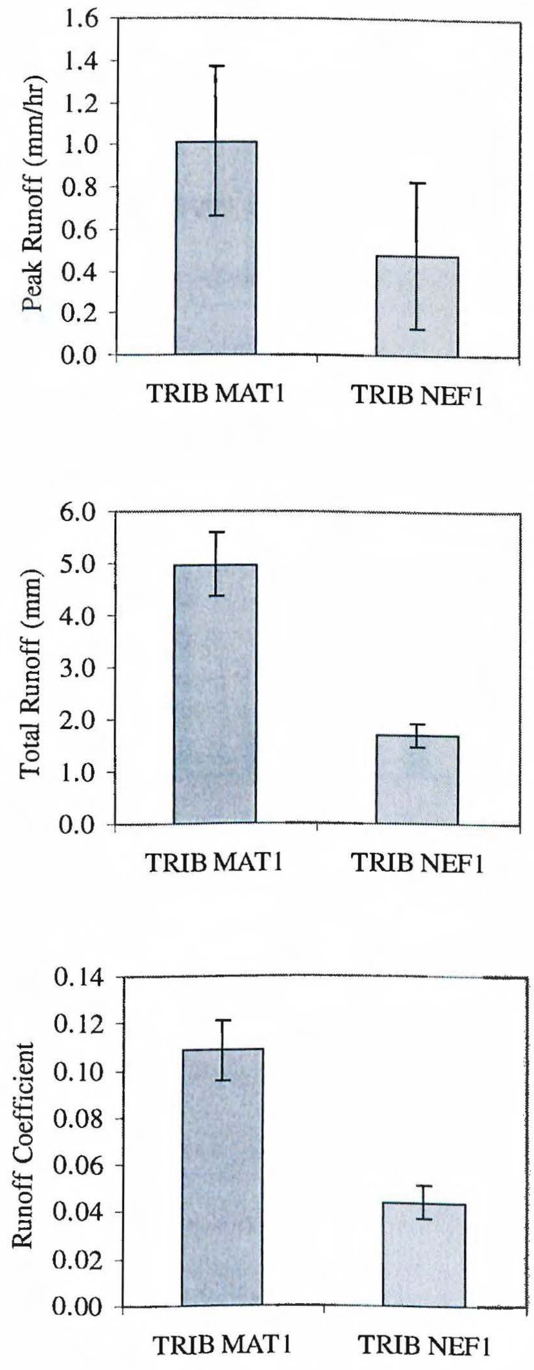



Figure 14. Mean watershed response characteristics (± s.e.) for the eight most intense storms at the MAT1 and NEF1 watersheds between May and October 1999 to 2001.

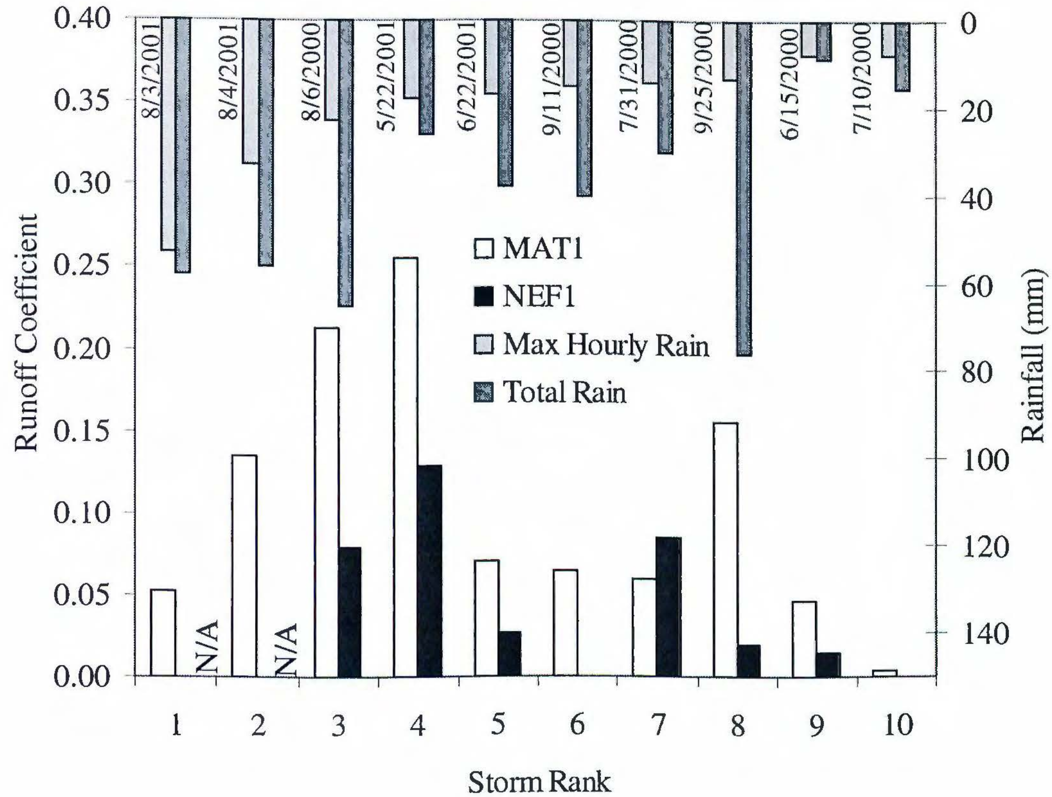



Figure 15. Runoff coefficients and maximum rainfall intensities for the 10 most intense storms at the MAT1 and NEF1 watersheds between May and October 1999 to 2001.

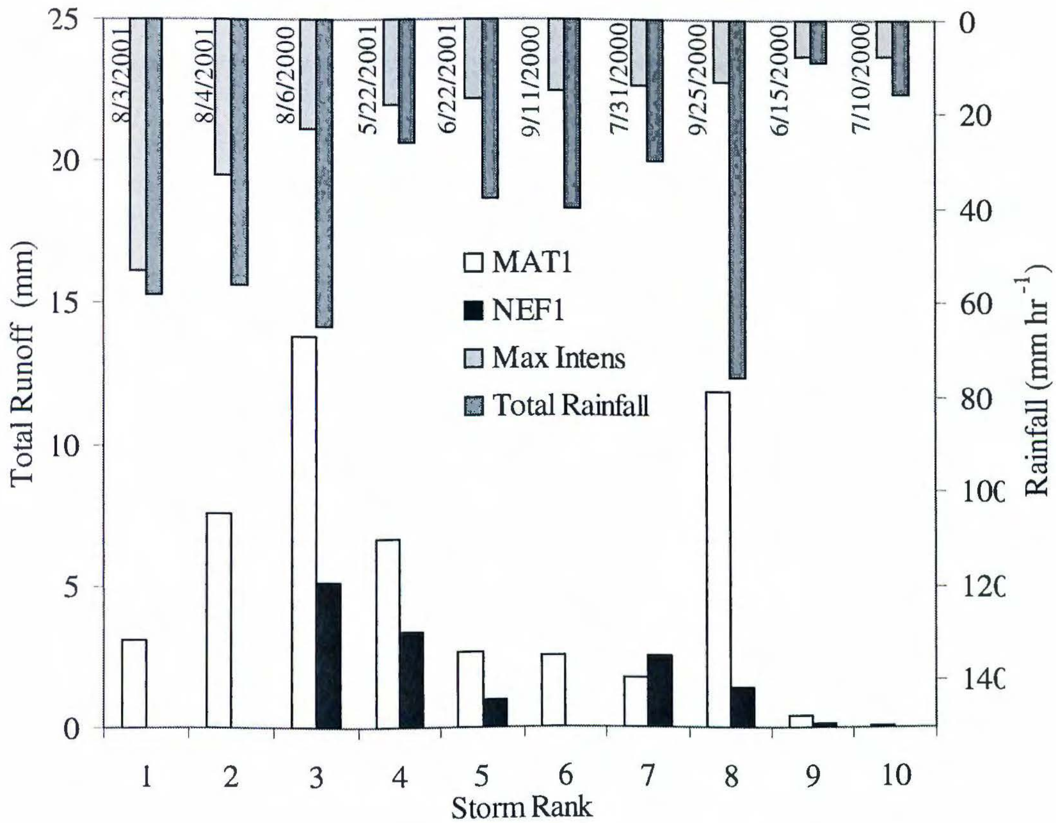



Figure 16. Total event runoff and maximum rainfall intensities for the 10 most intense storms at the MAT1 and NEF1 watersheds between May and October 1999 to 2001. Excludes 2 storms at NEF1 when animals disrupted the gage.

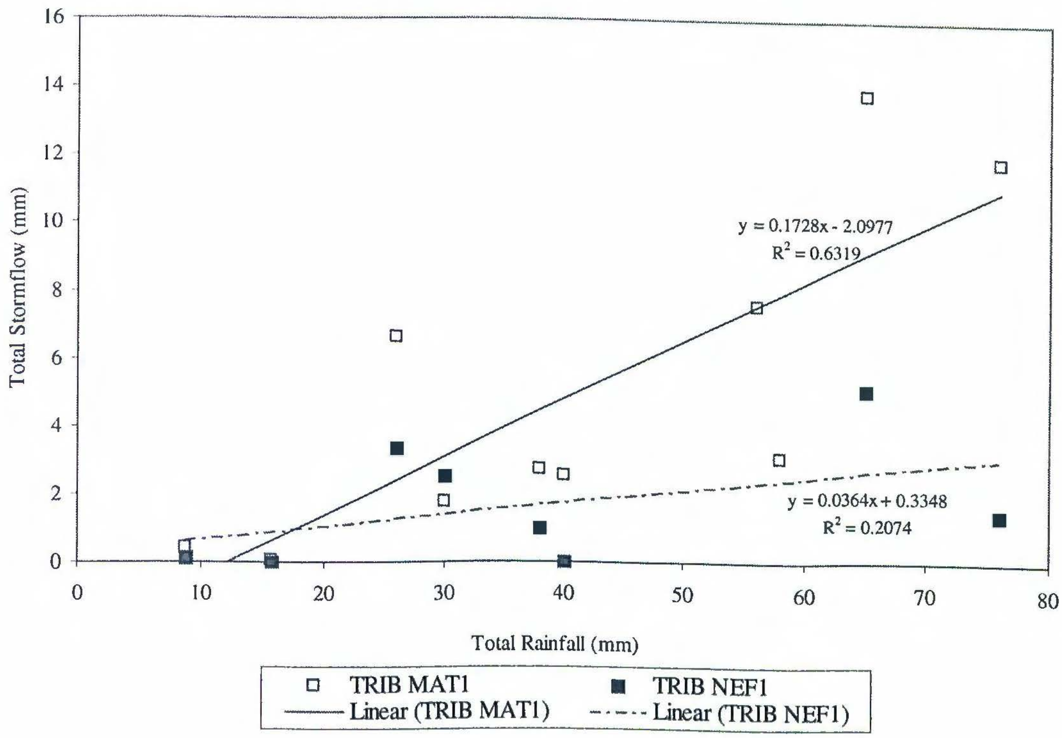



Figure 17. Relationship between total rainfall and total stormflow for the 10 most intense storms (May thru October) from 1999 to October 2001 at MAT1 (□) and NEF1 (■)

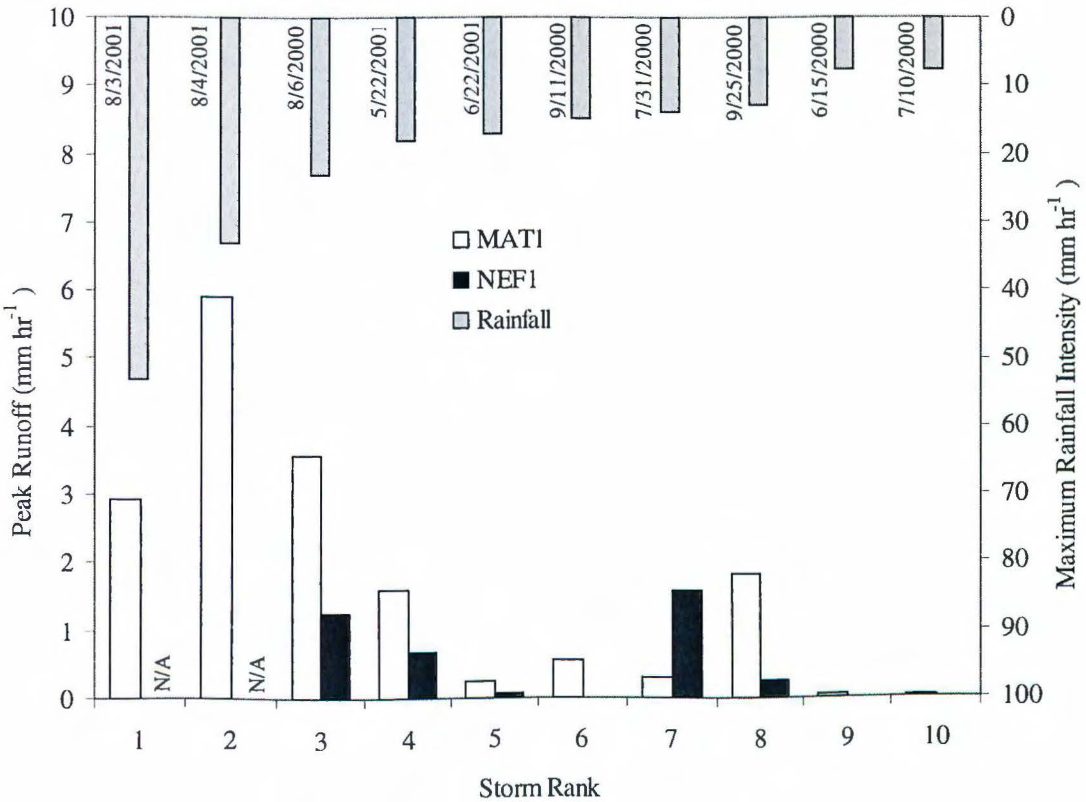



Figure 18. Peak runoff and maximum rainfall intensities for the 10 most intense storms (May thru October) from October 1999 to October 2001. Excludes two storms in August 2001 due to equipment problems at NEF1.

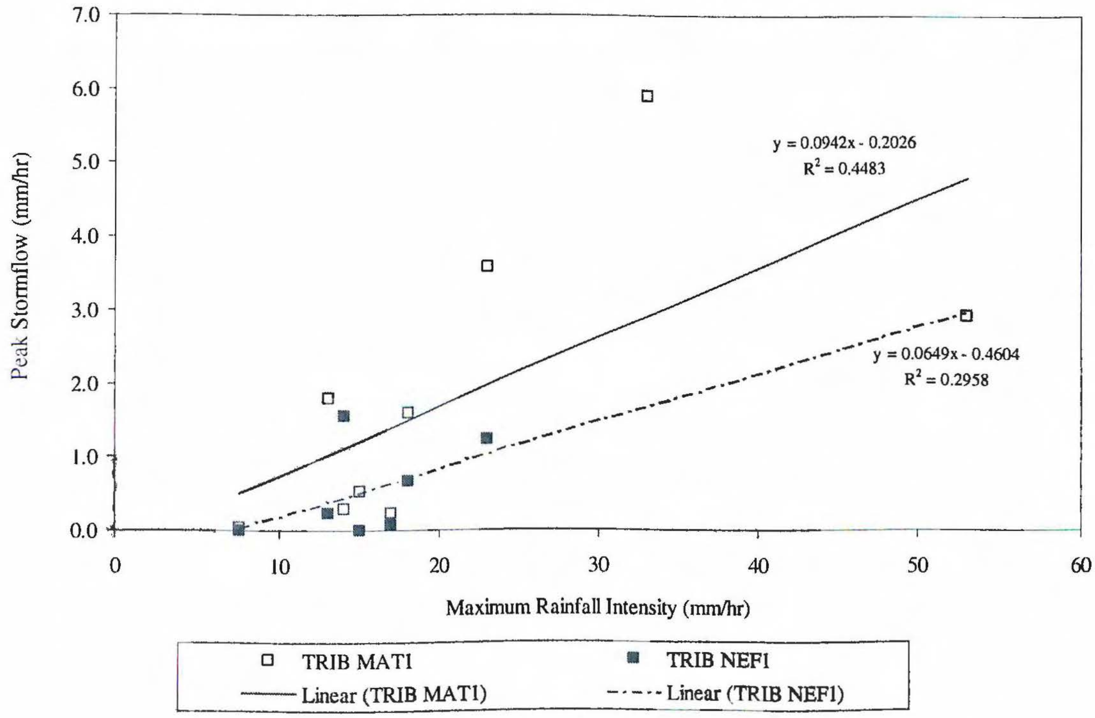



Figure 19. Relationship between maximum hourly rainfall intensity and peak stormflow for the 10 most intense storms (May thru October) from 1999 to October 2001 at MAT1 (□) and NEF1 (■).

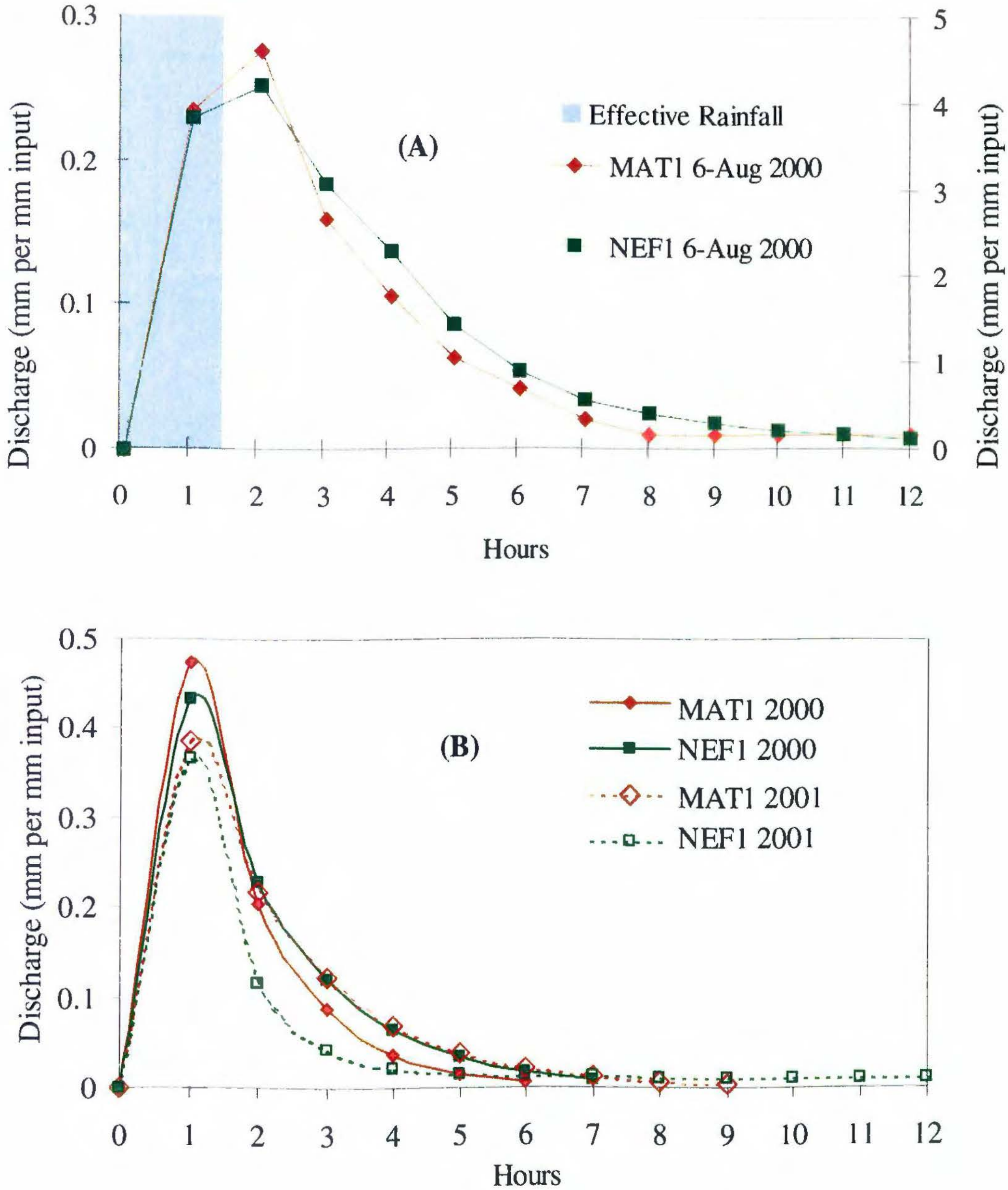



Figure 20. Two-hour unit hydrographs (A) for a thunderstorm (6 August 2000) and one-hour unit hydrographs from June to October 2000 and 2001.

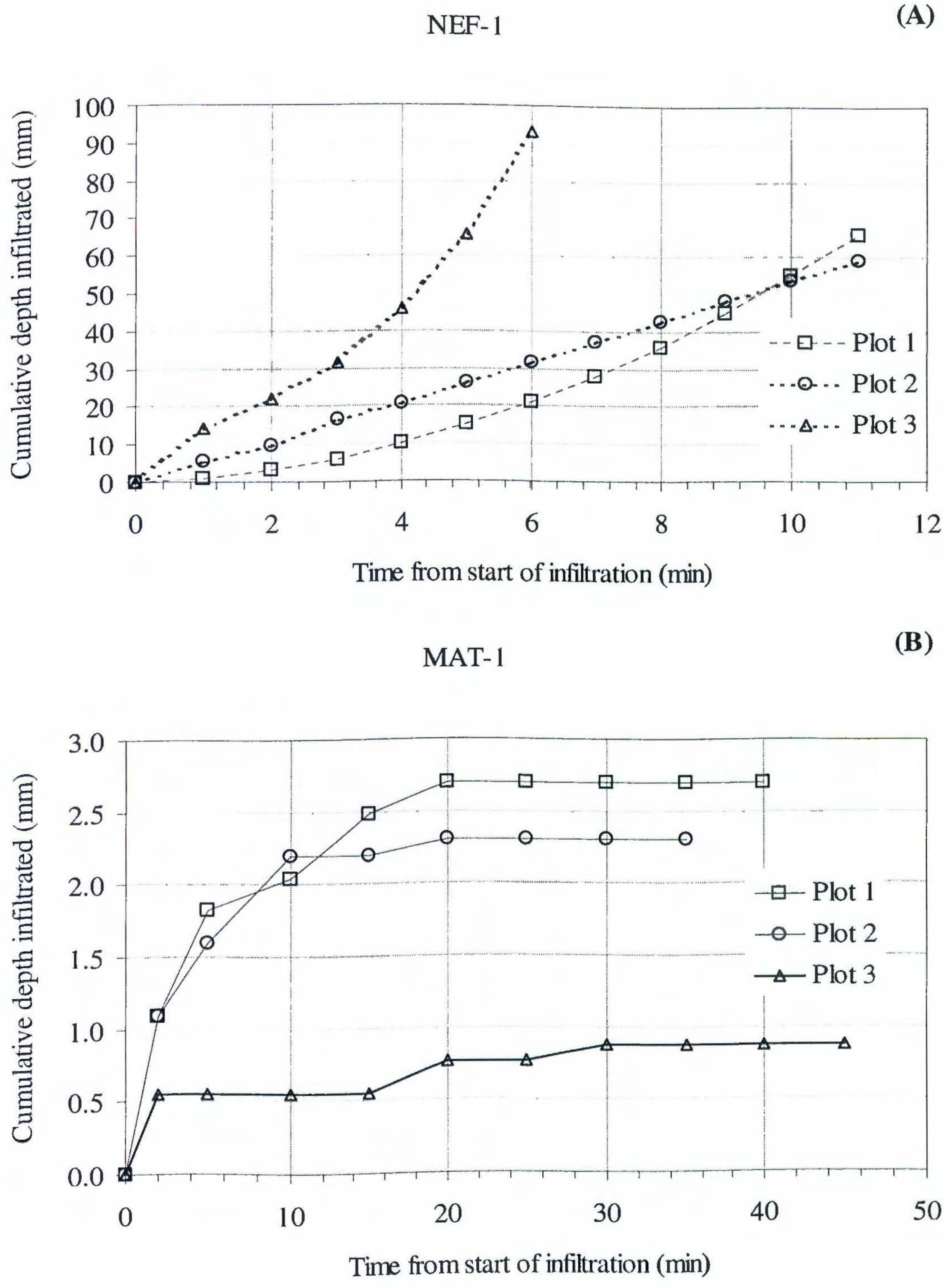



Figure 21. Cumulative depth of water infiltrated at each of three plots at MAT1 (A) and NEF1 (B).

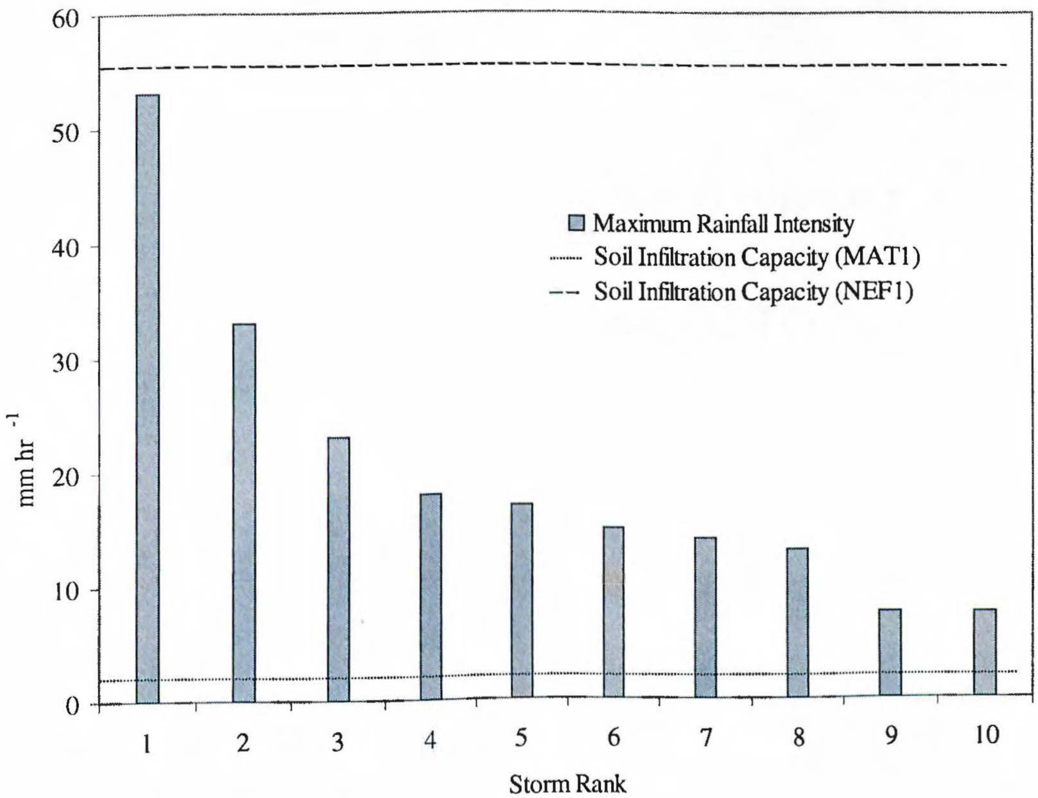



Figure 22. Maximum hourly rainfall intensity versus soil infiltration capacities at MAT1 and NEF1.

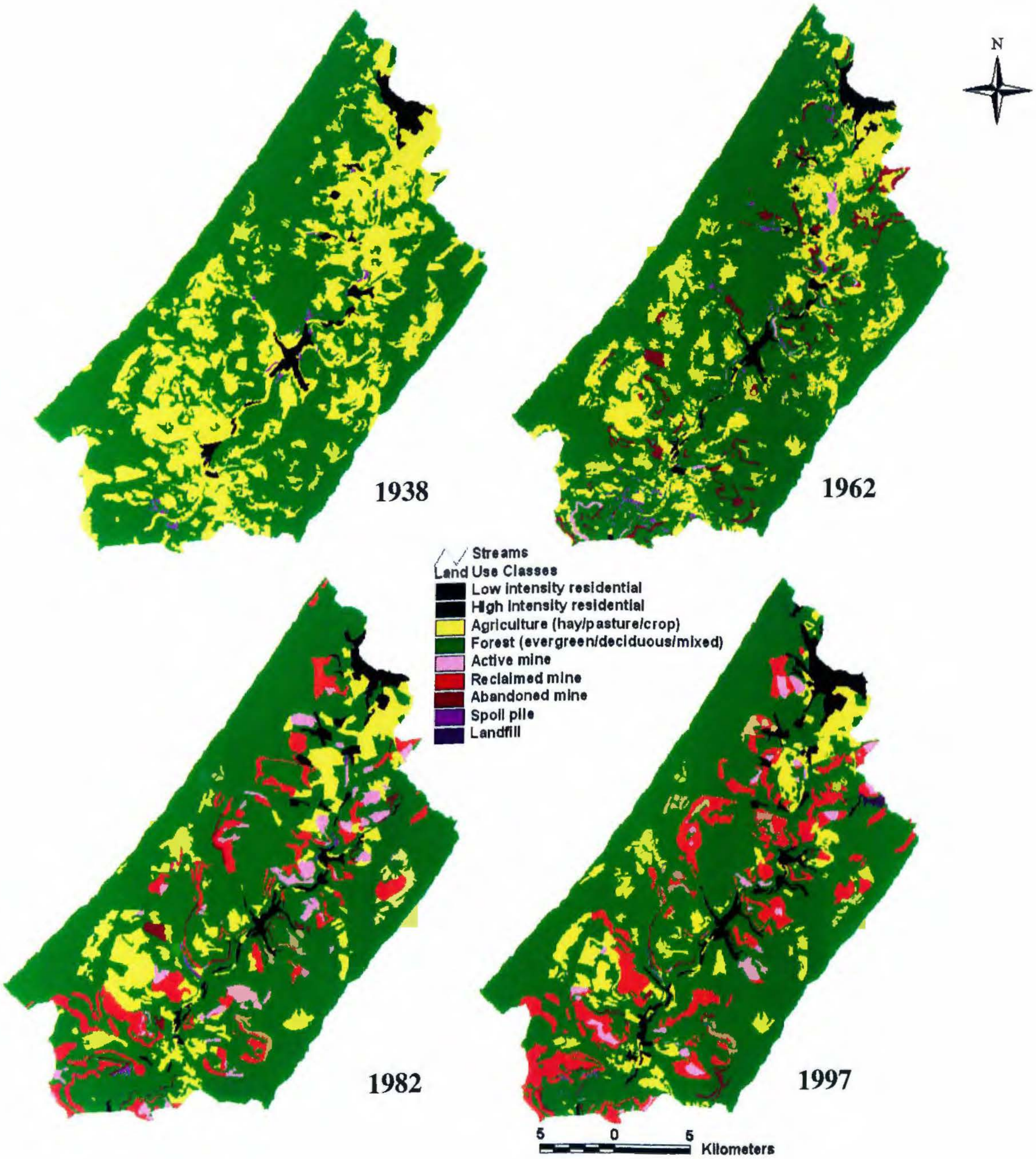



Figure 23. Results of LULC change over time in the Georges Creek watershed in western, Maryland from 1938 to 1997.

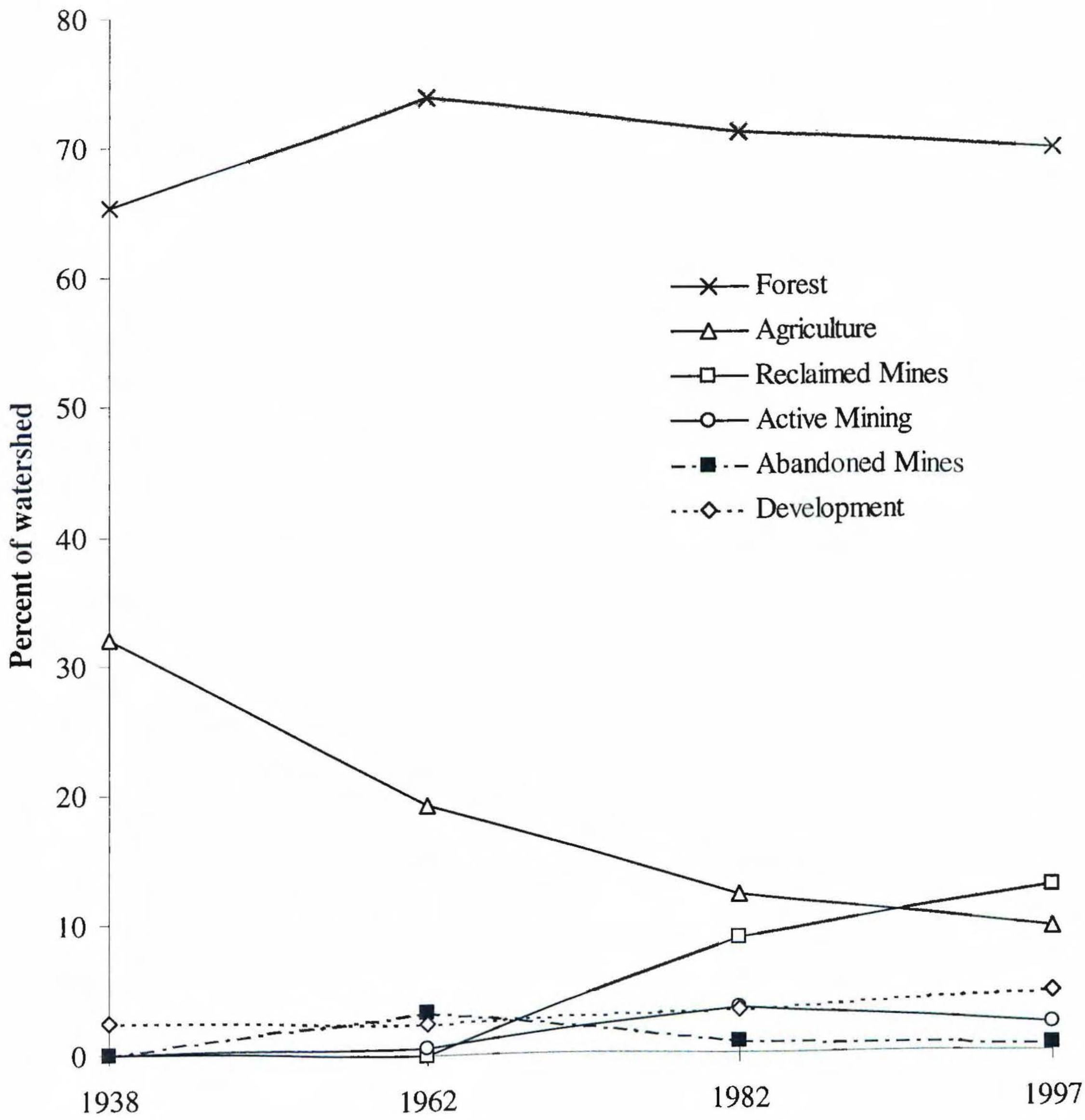



Figure 24. Primary LULC changes for each of the major classes in the Georges Creek basin, 1938 to 1997.

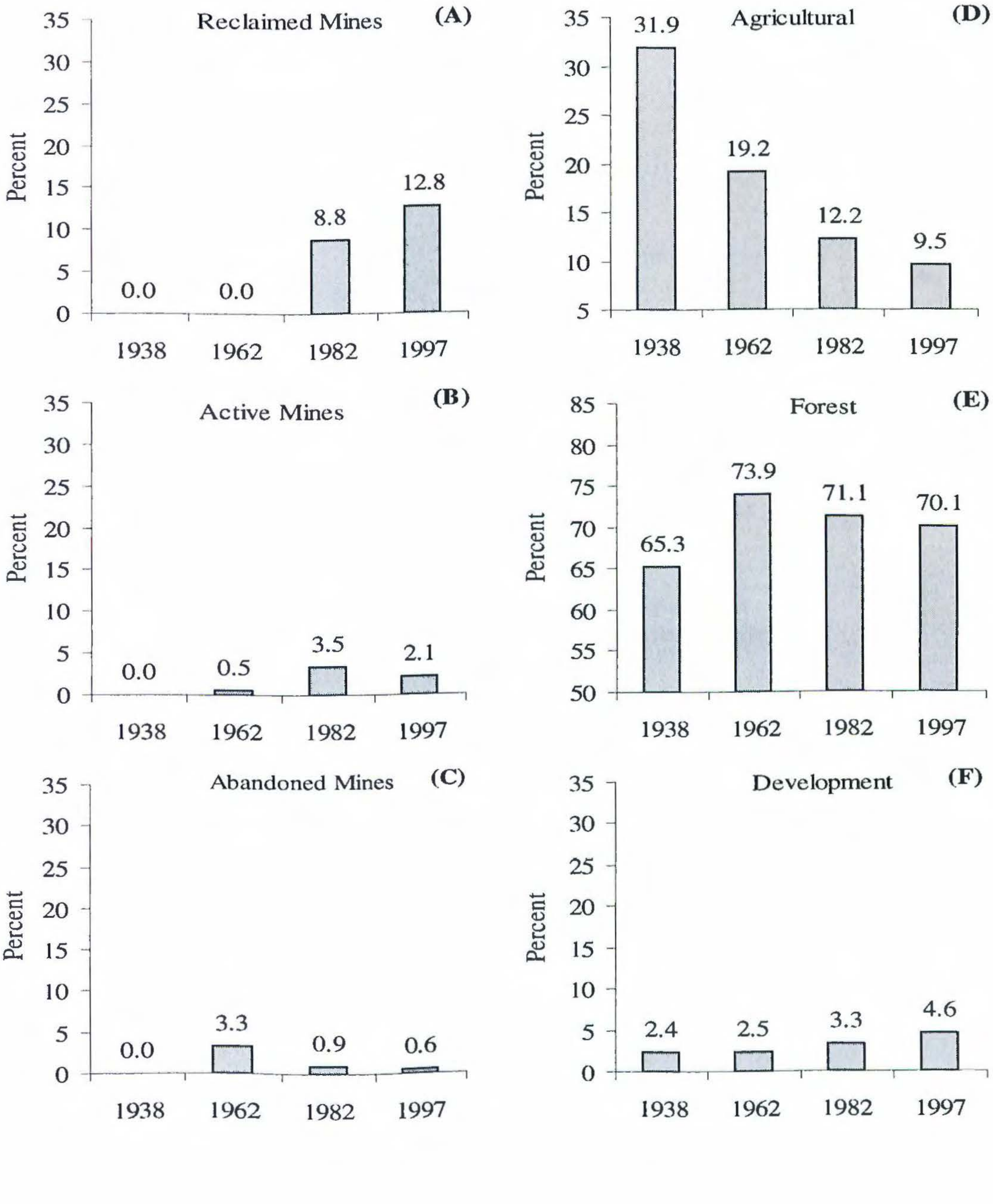



Figure 25. LULC changes by class in the Georges Creek watershed (1938-1997). Values represent percentage of the entire watershed.

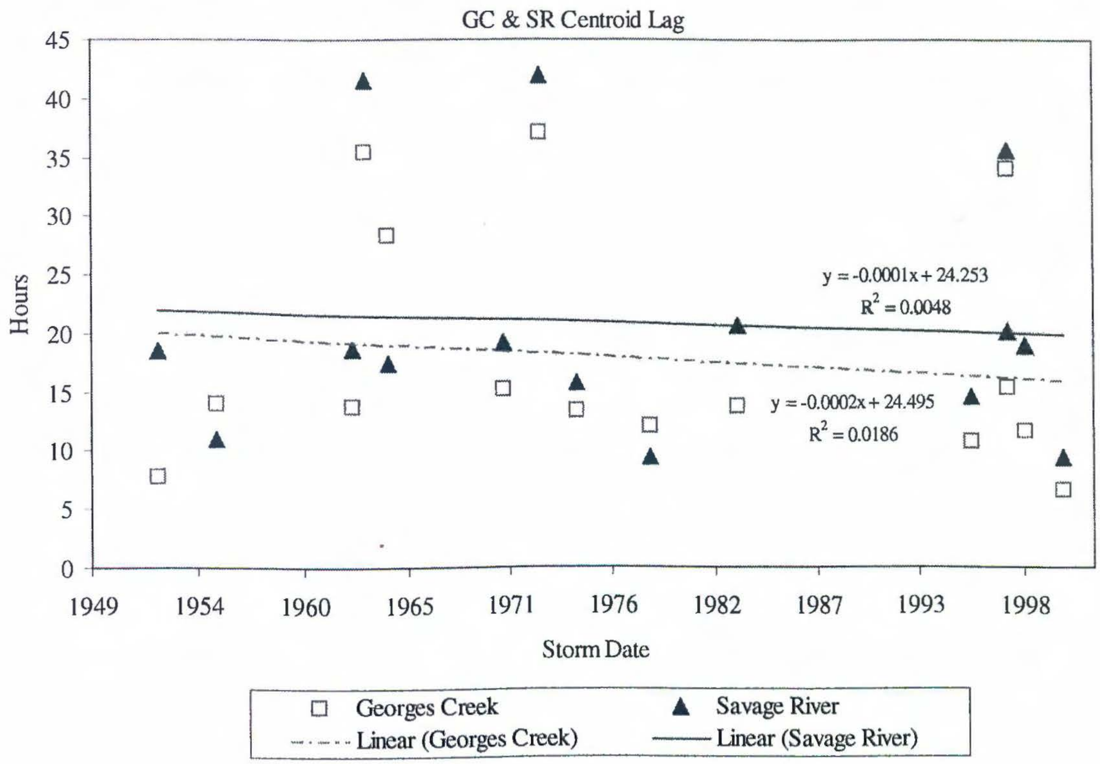



Figure 26. Centroid lag and trend lines for the 15 selected storms in the Georges Creek (□) and Savage River (▲) watersheds (1952-2000).

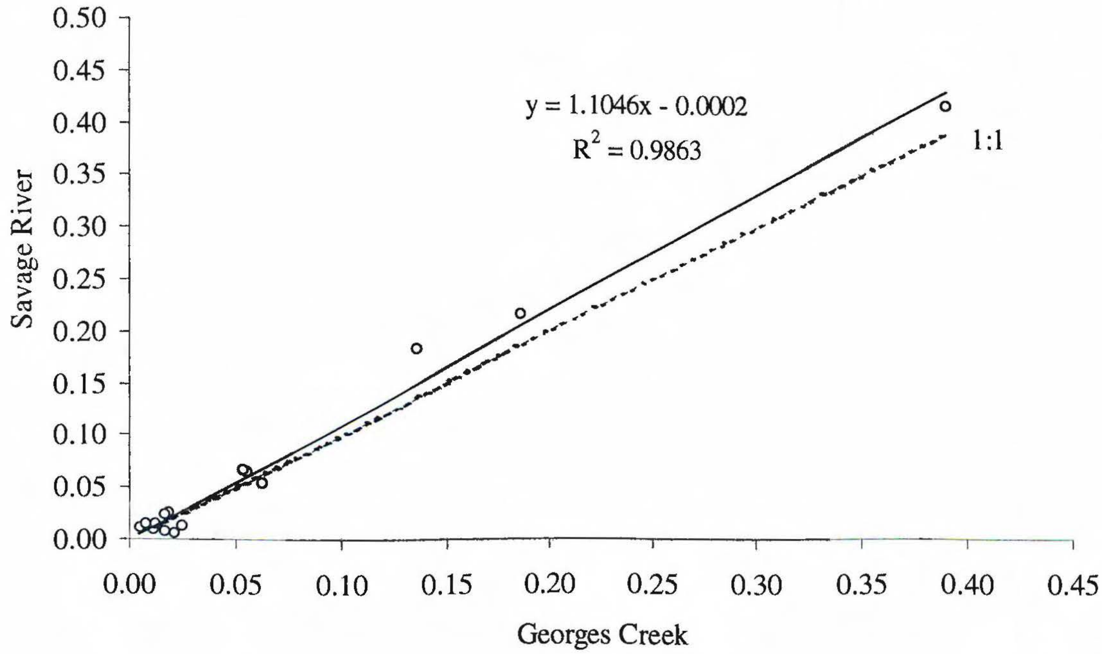



Figure 27. Correlation between runoff ratios for Georges Creek and Savage River watersheds for 15 selected storms of relatively uniform intensity and distribution (1952 – 2001)

Table 3. Number of LULC patches, % of watershed, mean area, and total area in each LULC class for the Georges Creek watershed, western Maryland (1938-1997).

| **Land Use Class** | **1938** | | | | **1962** | | | | **1982** | | | | **1997** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Area (ha)** | | | | **Area (ha)** | | | | **Area (ha)** | | | | **Area (ha)** | |
| (LU code) | # | % | *Mean* | *Total* | # | % | *Mean* | *Total* | # | % | *Mean* | *Total* | # | % | *Mean* | *Total* |
| Development | | | | | | | | | | | | | | | | |
| *Low intensity (2)* | 13 | 0.6 | 8.9 | 108 | 36 | 0.8 | 4.4 | 158 | 33 | 1.6 | 9.0 | 296 | 37 | 2.5 | 12.6 | 464 |
| *High intensity (3)* | 8 | 1.8 | 43.0 | 343 | 8 | 1.6 | 38.0 | 304 | 8 | 1.8 | 41.5 | 331 | 8 | 2.2 | 50.8 | 406 |
| Agriculture (5) | 152 | 31.9 | 39.4 | 5992 | 389 | 19.2 | 9.3 | 3608 | 111 | 12.2 | 20.7 | 2294 | 132 | 9.5 | 13.6 | 1792 |
| Forest (10) | 74 | 65.3 | 165.9 | 12268 | 97 | 73.9 | 143.0 | 13880 | 24 | 71.1 | 556.6 | 13359 | 39 | 70.1 | 337.7 | 13164 |
| Surface Mining | | | | | | | | | | | | | | | | |
| *Active (13)* | 0 | 0.0 | 0.0 | 0 | 31 | 0.5 | 5.9 | 97 | 53 | 3.5 | 12.3 | 651 | 47 | 2.1 | 8.5 | 399 |
| *Abandoned (14)* | 0 | 0.0 | 0.0 | 0 | 124 | 3.3 | 5.0 | 617 | 20 | 0.9 | 8.2 | 164 | 25 | 0.6 | 4.2 | 105 |
| *Reclaimed (15)* | 0 | 0.0 | 0.0 | 0 | 0 | 0.0 | 0.0 | 0 | 72 | 8.8 | 22.9 | 1649 | 105 | 12.8 | 23.5 | 2400 |
| Spoil (16) | 33 | 0.4 | 2.2 | 70 | 97 | 0.6 | 1.2 | 116 | 14 | 0.2 | 2.6 | 36 | 26 | 0.1 | 0.8 | 19 |
| Landfill (17) | 0 | 0.0 | 0.0 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 0.0 | 0.0 | 0 | 1 | 0.2 | 31.2 | 31 |
| **Total** | | **100** | | **18781** | | **100** | | **18781** | | **100** | | **18781** | | **100** | | **18781** |

## Chapter IV: DISCUSSION

Results from this study indicate that surface mining and reclamation has the potential to impact the hydrological responses of watersheds, especially small watersheds where a relatively large percentage of the watershed area has been mined. At the small watershed scale, the watershed response to total rainfall was significantly different from the response of a forested reference watershed that was otherwise physically similar. However, when comparing only the unit response of each watershed to effective rainfall inputs, both catchments behaved very similarly. In general, the differences in hydrological response between the partially surface mined and reclaimed watershed and the entirely forested could be underestimated based on a number of factors. As watershed scale increases however, these differences in hydrologic response observed at a small scale are apparently much less detectable due to either natural variations, or attenuation as water is routed through larger channels downstream.

On an annual basis, the surface mined and reclaimed watershed produced similar water balances to that of the forested watershed. This occurred regardless of higher total event runoff at MAT1. NEF1 however produced baseflow during the spring months when MAT1 did not, making the overall annual water balances similar. Annual runoff yields and evapotranspiration rates are similar to the zero order watersheds in a study by Burges et al. (1998) where they compared a previously logged and reforested watershed to a suburban watershed. In that comparison the runoff yields were lower at their forested reference site (12 %) than the suburbanized site (44%). In comparison, in this study annual runoff yields at the reference site were approximately 25% compared to 26% at the reclaimed mine.

While results of this study indicate that the watersheds produced similar responses when averaged over an entire water year, the responses to individual storms were significantly different, primarily in the amount of rainfall abstracted (i.e., water that never reaches the watershed outlet) during any given storm. The amount of rainfall abstracted was greatly reduced at the surface mined and reclaimed watershed relative to the forested reference site. This decrease in rainfall abstraction at MAT1 has a number of consequences including significant differences in peak runoff, runoff ratios, and total runoff. Runoff ratios and total runoff for rain events occurring at the surface mined and reclaimed watershed were significantly higher that at the forested watershed. This finding is supported by the results of Schueler (1994) who observed that increasing the imperviousness of a watershed by 35%-50% can result in as much as a 20% increase in runoff. After the rate of rainfall abstraction has been exceeded and effective rainfall was produced, both watersheds responded in a surprisingly similar manner to a unit impulse of effective rainfall. Both watersheds produced unit hydrographs that were nearly identical in both the timing and geometric shape. As each watershed was subjected to a unit of effective rainfall, both watersheds exported that volume (or pulse) of rainfall at very similar rates.

There are a number of possible explanations for the observed differences in rainfall abstraction at each of the small watersheds including a) altered soil characteristics and b) altered LULC (Hornbeck et al. 1970, Burton 1997). At MAT1, it appears that surface mining and reclamation likely resulted in highly compacted soils with high bulk density and low infiltration rates. Furthermore, clays (at least at MAT1) brought to the surface during reclamation have the potential to inwash, or clog surface pores in the soils, further reducing infiltration rates. In addition to altering soil hydrologic properties, intense vegetation removal nearly 15 years ago has resulted in a cleared area that is now covered with dense grasses capable of influencing evapotranspiration and throughfall rates.

One of most obvious explanations for decreased rates of abstraction at MAT1 is the physical soil properties. Extreme soil compaction has greatly suppressed infiltration capacities at MAT1 to less than 1 cm/hr, compared to nearly 55 cm/hr at the reference watershed. These low infiltration capacities at the MAT1 plots are typical of results from several other studies on reclaimed surface mines that have found infiltration rates near or less than 1 cm/hr (Chong and Cowsert 1997; Guebert and Gardner 2001). In addition to low infiltration capacities, soil bulk density was also greater as a result of compaction. At MAT1 soil bulk density was 1.43 g/cm$^3$ compared to 0.98 g/cm$^3$ at NEF1 (Currie et al. unpublished data). The low infiltration capacities at MAT1 and the fact that in all the 10 storms analyzed maximum rainfall intensities at MAT1 consistently exceeded the maximum rate at which rainfall could infiltrate the soil surface suggest that the dominant runoff mechanisms at MAT1 are likely a) Hortonian overland flow and/or b) saturation overland flow. Saturation overland was more likely to be an important factor in runoff generation for storms of longer duration or storms where antecedent moisture conditions were high. The small amount of rainfall that was abstracted during these storms was most likely due to storage in the various depressional ponds that developed as the surface mine subsided.

In contrast, soil physical properties were very different at the NEF1 watershed, which abstracted considerably more rainfall per storm than the MAT1 watershed. Even though NEF1 yielded a unit hydrograph very similar to MAT1, effective rainfall could not have been exported as surface runoff via the same mechanism. Recall that soils at NEF1 are deep, well-drained, and capable of quickly abstracting rainfall. In fact, according to the infiltration capacity curves at NEF1, a rainstorm of nearly 55 cm/h would be required to exceed the soil infiltration capacity (Figure 22)! During this study, the soil infiltration capacity at NEF1 was never exceeded suggesting that after the soil was wetted soil water was quickly routed to the stream channel via a subsurface stormflow mechanism. This mechanism is well documented in the literature (Whipkey et al. 1965, Hewlett and Hibbert 1967, Freeze 1974, Beven and Germann 1982). In fact, in order for the unit hydrographs to be as similar as they are, subsurface stormflow at NEF1 must be routed as quickly to the stream channel as it is via overland flow at MAT1.

One unusual observation in the relationship between infiltration capacity and runoff generation in this study requires some discussion. In particular, the cumulative depth of water infiltrated into the soil typically increases at a decreasing rate (i.e. the infiltration capacity is very high at the beginning of the curve and decreases over time) due to the initial negative pressure head caused by capillary pressure. At NEF1 however, infiltration capacity curves tended to remain linear throughout the experiment, with no decrease in infiltration rate. One likely explanation for this anomaly is that measurements of infiltration capacity were made in a year that was relatively wet. At the time of measurement total precipitation for the year (January to June) was nearly 74 mm (3 in) above average. In addition, soils had been wetted by an intense thunderstorm 2 days earlier that had added 20 mm (0.8 in) of rainfall. This thunderstorm may have been sufficient enough to wet the soils and reduce the capillary pressure head. This anomaly, however, does not affect the overall interpretation of the large difference in infiltration capacities observed at the two sites.

In addition to the effects of soil properties on runoff generation, the difference in LULC is the second most obvious difference between the two watersheds that is responsible for observed differences in the hydrologic responses of MAT1 and NEF1. Roughly 46% of MAT1 has undergone extensive vegetation removal and is currently covered by tall grasses or patchy areas of bare soil. On one hand, woody vegetation removal normally decreases evapotranspiration back since roots are not longer transpiring, causing more water to leave the watershed as surface runoff. On the other hand, it should be noted that the lack of woody vegetation at MAT1 increases exposure to wind and solar radiation, which is undoubtedly increasing the evaporative demand at MAT1 (Swift et al. 1975). Therefore, although transpiration rates may be decreased by vegetation removal, evaporation rates may make up the difference in loss to the atmosphere. This would explain the similarities in evapotranspiration rates in the annual water budgets for the two watersheds.

Observed differences in watershed response may be even greater when considering a number of factors that make estimates of the hydrologic response at MAT1 conservative. It is suggested that these estimates when compared to the reference watershed are conservative based on the fact that a) MAT1 is not entirely surface mined and reclaimed; b) the slope of MAT1 is not as steep as NEF1 and; c) MAT1 is larger than NEF1. It is expected that the runoff differences would be even greater if MAT1 was as steep as NEF1. Furthermore, estimates of runoff from the reclaimed area of MAT1 are probably low, since watershed outflow is actually an average of runoff produced on the two different types of landcover in the watershed (45% reclaimed and 55% percent forested). Although one would expect the reclaimed area to produce more runoff than the forested area, future research should be aimed at resolving uncertainties in these two contributing areas.

It should be noted that although no statistically significant ($p \leq 0.05$) difference was detected in the timing of response (centroid lag) between the two small watersheds it is likely an artifact of the stream gage resolution. Stream gages used in this study were only accurate to $\pm$ 1 hr, which is likely too coarse resolution for these watersheds. Considering that these watersheds respond on average within 3 hr of the center of rainfall mass, differences in response times may only be detectable with gages that can monitor flow changes on the order of minutes.

It was expected that Georges Creek would be more responsive to rainfall events than Savage River based on the differences in LULC and amounts of impervious area. However, characteristics such as peak runoff, total runoff, and runoff ratios were not significantly different between the two watersheds. Results of the larger basin (Georges Creek and Savage River) study were different than originally hypothesized, regardless of a 13% increase in surface mine reclamation in the Georges Creek watershed since 1977. Based on an analysis of 15 storms, Georges Creek was found to be substantially flashier than Savage River, but no statistically significant difference in the hydrological response characteristics of the two basins could be detected. In addition, no significant trends could be found over time.

On average, the Georges Creek watershed responded 3 hours more quickly (center of mass to center of runoff) than the Savage River watershed. This is a particularly interesting considering it is the only watershed response characteristic that significantly differs between the two watersheds. In fact, this difference may be even greater and more significant when considering that observations on the timing of rainfall were made in the Savage River watershed. Since the majority of storms approach from the west (prevailing wind) and cross over the Savage River watershed before reaching Georges Creek, the Savage River should respond sooner than the Georges Creek watershed (all else being equal). Storms could conceivably arrive in the Georges Creek and hour or more after occurring in the Savage River watershed. This estimate could mean that Georges Creek may actually respond nearly 4 hours more quickly than the Savage River watershed.

There are several possible explanations why the hydrological effects of surface mining and reclamation observed at the small watershed scale were not observed at the larger basin scale. Two possible explanations deal with a) data quality and availability and; b) LULC heterogeneity and other physical watershed properties. Based on the criteria used in this study to select representative storms, the availability of storms was restricted to 15 events that occurred over each basin. Additional storms would improve statistical power. In addition, this study would benefit from increased spatial resolution for estimates of areal precipitation. The main rain gage used in this analysis was located in the Savage River watershed. These watersheds are located in mountainous terrain subject to orographic effects, however. In addition, Georges Creek basin is separated by the gage at Savage River Dam by Big Savage Mountain. Since many of the storms in this area approach from the west, Georges Creek may experience a rainshadow effect from Big Savage Mountain, causing actual precipitation depths to be lower than those measured in Savage River. A comparison of the long-term water balances for the Georges Creek and Savage River basins supports this observation as well. In general, Georges Creek tends to yield over 100 mm less runoff than Savage River, probably a result of less rainfall occurring within the watershed or from loss to the Hoffman Drainage Tunnel.

The heterogeneity in LULC may also have confounded analyses aimed at correlating LULC change with hydrological responses. This study is one of few that investigate the long-term changes in streamflow trends with changes in watershed LULC. Gebert and Krug (1996) performed a similar analysis in Wisconsin's "Driftless Area" (non-glaciated) where they investigated trends in streamflow characteristics for watersheds with various LULC histories. The study found that in forested areas no trends were observed in streamflow characteristics. However, the study also found that in predominantly agricultural areas, annual flood peaks increased while annual seven-day low flows decreased. The authors attributed this change to improved agricultural practices that decreased compaction and runoff from agricultural lands. Similar responses may be occurring in the Georges Creek watershed that effectively counterbalance any increases in runoff observed at the small watershed sites. At the same time forest regeneration has occurred, agricultural land has decreased, and stormwater management is improving in the basin, all of which are likely reducing runoff.

Another possible explanation for the lack of difference in watershed responses despite very different LULC may be the differences in watershed physical properties. In general, Savage River is a steeper watershed (12 degrees compared to 9.5 degrees in Georges Creek). Infiltration tends to decrease and overland flow tends to increase with increasing slope (Dingman 1994). In addition, Savage River may be responding more readily to rainfall than Georges Creek due to its slightly higher drainage density (0.77 and 0.69, respectively) which is a measure of how efficiently the watershed is drained by streams. The Hoffman Drainage Tunnel, constructed in 1907 drains groundwater from the Georges Creek watershed and discharges into the Braddock Run watershed (an adjacent basin). The tunnel is approximately two miles long and drains approximately 36 $km^2$ of the Georges Creek watershed (Maryland Department of Natural Resources 2001). As a result, estimates of annual runoff as well as event runoff for Georges Creek are lower due to loss to the Tunnel. Unfortunately, useful estimates of how much water that is diverted are lacking.

One way to address the non-uniform spatial distribution of rainfall would be to incorporate NEXRAD (NEXt Generation RADar) data, formerly known as WSR-88D (Weather Surveillance Radar-1988 Doppler). NEXRAD utilizes a suite of algorithms to generate real-time precipitation depths over an area with spatial resolutions from 4 to 8 km (French and Krajewski 1994). Current NEXRAD technology is capable of sensing rainfall at resolutions as fine as 1 $km^2$. This data could then be coupled with a DEM in GIS where a cell-by-cell comparison could be conducted between elevation and precipitation. NEXRAD has a number of limitations, however. Some research has indicated that radar underestimates precipitation when compared to traditional rain gage estimates (Smith et al. 1996). In addition, the ability of NEXRAD to provide information about historical rainfall distribution is limited. Smith and Krajewski (1991) argue that only rain gage and radar data from the same time period be used for this relationship. Even though the actual quantities may not be precise, NEXRAD would provide useful information on the spatial patterns of precipitation within the watersheds.

Improved spatial resolution of rainfall data could conceivably increase the ability of IHACRES to model unit hydrographs for each of the watersheds as well. In fact, IHACRES may be the best justification of the need for more spatially explicit data, specifically areal rainfall estimates. Initially, it was proposed that IHACRES would be used to deconvolve unit hydrographs to examine differences in watershed response due primarily to LULC change. However, IHACRES generated fatal errors while trying to model streamflow, suggesting that rainfall estimates for the watershed may be inadequate. This has been observed in other studies that have found IHACRES to be highly sensitive to the density of rain gages in a watershed (Hansen et al. 1996, Schreider et al. 1996, Andreassian et al. 2001). Incorporating NEXRAD into a model that generates spatially explicit estimates of rainfall depths may increase the ability to scale hydrologic responses observed at the small catchments to the larger basins.

## Chapter V: CONCLUSIONS

The primary goal of this study was to determine whether small watersheds subjected to mine reclamation practices display a stormflow response to rain events that is different from those displayed by similar watersheds that are covered by typical second-growth forests. A secondary goal was to investigate whether intensive surface mining in the Georges Creek watershed of western Maryland has appreciably altered the stormflow response at the larger river basin scale. Based on intensive field hydrological measurements at the small watersheds, LULC data obtained from digitized aerial photographs from 1938 to 1997, and historical precipitation and streamflow data, results from this study indicate that surface mining and reclamation can impact the hydrological responses of watersheds, especially small watersheds where a relatively large percentage of the watershed area has been mined.

At a river basin scale however, regardless of a 13% increase in surface mine reclamation in the Georges Creek basin since 1977 very little difference in stormflow response characteristics was observed. Georges Creek was found to be substantially flashier than Savage River, but no statistically significant difference in the hydrological response characteristics of the two basins could be detected. In addition, no significant trends could be found over time. The lack of response was different than hypothesized and may be the result of a number of factors that hinder scaling the runoff responses observed at the small watershed scale to the larger river basin scale. Finally, I believe there is a need to conduct watershed studies of runoff generation on a variety of reclaimed mines that are representative of the diversity of reclamation practices that have actually been employed in western Maryland and at other locations where flooding may be a major concern. Based on the findings in this study, it is critical that future research, land management, and watershed planning decisions consider the relationship between surface mining and hydrological response in the Georges Creek watershed as well as other similar watersheds.

Appendix I. Coordinates of watersheds and gages

| | Latitude | Longitude | Area |
|---|---|---|---|
| **Watersheds** | | | |
| MAT1 | 39° 35' 39" N | 78° 53' 29" W | 27 ha |
| NEF1 | 39° 35' 47" N | 78° 54' 29" W | 3 ha |
| EBNR | 39° 36' 01" N | 78° 54' 06" W | 104 ha |
| Georges Creek (as gaged at Franklin) | 39° 35' 00" N | 79° 00' 00" W | 187.6 $km^2$ |
| Savage River (as gaged near Barton) | 39° 35' 00" N | 79° 05' 00" W | 127.2 $km^2$ |
| **Gage Locations Used** | | | |
| MAT1 | 39° 35' 32" N | 78° 53' 49" W | |
| NEF1 | 39° 35' 54" N | 78° 54' 13" W | |
| EBNR | 39° 35' 52" N | 78° 54' 38" W | |
| Georges Creek at Franklin | 39° 29' 38" N | 79° 02' 42" W | |
| Savage River Near Barton | 39° 34' 05" N | 79° 06' 10" W | |

Appendix II. LULC classes, codes, and id key

| | |
|---|---|
| Class 1: Low intensity developed | LuCode: 2 |
| Class 2: High intensity developed | LuCode: 3 |
| Class 3: Agriculture (hay/pasture/crop) | LuCode: 5 |
| Class 4: Forest (evergreen/deciduous/mixed) | LuCode: 10 |
| Class 5: Active surface mines | LuCode: 13 |
| Class 6: Abandoned surface mines | LuCode: 14 |
| Class 7: Reclaimed surface mines | LuCode: 15 |
| Class 8: Spoil (tailings) | LuCode: 16 |
| Class 9: Landfill | LuCode: 17 |

LULC classes were divided into their respective classes with the following descriptions (adapted from the Multi-Resolution Land Characteristics Consortium-MRLC):

Class 1: Low intensity developed (approximately 50 – 80% constructed material; approximately 20-50% vegetation cover; generally a high percentage of residential development).

Class 2: High intensity developed ( 80 – 100 % constructed material; less than 20 % vegetation; generally commercial development or dense residential).

Class 3: Agriculture (areas that are primarily hayed or grazed. Includes pastures, row crops, and hay).

Class 4: Forest (greater than 50% forest cover; includes a wide grouping of forest types: deciduous, conifers, both conifers and deciduous, forested wetlands, > 50 % revegetation on reclaimed mines).

Class 5: Active surface mines (areas currently being surface mined; visible coal seam, haul roads, and equipment).

Class 6: Abandoned surface mines (open pits; often scattered shrubs in pits; no mining equipment visible).

Class 7: Reclaimed surface mines (significant signs of recent reclamation; diversion ditches present; impressions in soil from reclamation equipment).

Class 8: Spoil (primarily from deep mines; tailings, gob piles, deep mine openings).

Class 9: Landfill (active landfilling; equipment and solid waste visible).

## Appendix III. PC-IHACRES Model Results

```
============================================================
MAT1 2000
IHACRES for WINDOWS, Version 1.02
FILE      : D:\PROGRAMS\IHACRES\MATTHEW\M2000.SUM
Date created              :02/26/02
Time created              :15:08:49
Record start date         :01/06/2000
Record start time         :01:00
Record end date           :27/09/2000
Record end time           :12:00
Record time interval :  1 hourly
Number of records    :      2844

CONTAINS : Summary of model results.
Reference Temperature =   20.00
Version 1.02,  Subperiod=  1,Range= 5857 to 8700(2844), Subints= 1,Time Delay=
1
   f     TauW    %Run    D     Bias     x1      u1   %ARPE  T.C.   A1    B0   Const
  1.00    90    12.22
  1.00    90    12.22 .682     .13     9.8      .0    .04  1.57 -.529 *****  .005
  1.00    90    12.22 .693     .19     1.8      .0    .05  1.23 -.442 *****  .005
  1.00    90    12.22 .694     .20      .5      .0    .06  1.17 -.426 *****  .005
  1.00    90    12.22 .694     .20      .4      .0    .06  1.17 -.424 *****  .005
  1.00    90    12.22 .694     .19     1.3      .0    .06  1.18 -.429 *****  .005
============================================================
MAT1 2001
IHACRES for WINDOWS, Version 1.02

FILE      : D:\PROGRAMS\IHACRES\MATTHEW\M2001.SUM
Date created              :02/26/02
Time created              :15:23:27
Record start date         :01/06/2001
Record start time         :01:00
Record end date           :25/09/2001
Record end time           :01:00
Record time interval :  1 hourly
Number of records    :      2785

CONTAINS : Summary of model results.
Reference Temperature =   20.00
Version 1.02,  Subperiod=  1,Range=14617 to17401(2785), Subints= 1,Time Delay=
1
   f     TauW    %Run    D     Bias     x1      u1   %ARPE  T.C.   A1    B0   Const
                           Tw(tk) is less than 1
  1.00     1
  1.00    11    14.95
  1.00    11    14.95 .614     .38    83.3     -.8    .02  2.09 -.619 *****  .007
  1.00    21    14.95
  1.00    21    14.95 .692     .35    72.9     -.6    .02  1.79 -.573 *****  .006
  1.00    31    14.95
  1.00    31    14.95 .720     .33    70.1     -.6    .02  1.70 -.556 *****  .005
  1.00    41    14.95
  1.00    41    14.95 .729     .31    69.5     -.6    .02  1.67 -.550 *****  .005
  1.00    51    14.95
  1.00    51    14.95 .730     .29    69.9     -.6    .02  1.67 -.549 *****  .005
  1.00    61    14.95
  1.00    61    14.95 .726     .27    70.7     -.6    .02  1.68 -.551 *****
.004
  1.00    71    14.95
  1.00    71    14.95 .720     .24    71.7     -.6    .02  1.69 -.554 *****
.004
  1.00    81    14.95
  1.00    81    14.95 .713     .22    72.9     -.6    .02  1.71 -.558 *****
.004
```

```
   1.00    91    14.95                                                                     
   1.00    91    14.95 .704    .20    74.1     -.6    .02  1.74 -.563 *****
 .004
 =========================================================

 NEF1 2000
 IHACRES for WINDOWS, Version 1.02
 FILE       : D:\PROGRAMS\IHACRES\TRBNEF1\N200SUM.SUM
 Date created             :02/26/02
 Time created             :15:08:49
 Record start date        :01/06/2000
 Record start time        :01:00
 Record end date          :27/09/2000
 Record end time          :12:00
 Record time interval :  1 hourly
 Number of records        :       2844

 CONTAINS : Summary of model results.
 Reference Temperature =  20.00
 Version 1.02,  Subperiod=  1,Range= 5857 to 8689(2833), Subints= 1,Time Delay=
 1
    f     TauW    %Run     D     Bias     x1      u1   %ARPE   T.C.    A1     B0   Const
  1.00    61    108.94
  1.00    61    108.94 .664     .14    10.6     .0    .04   1.58 -.531 3.400   .050

 =========================================================
 NEF1 2001
 IHACRES for WINDOWS, Version 1.02
 Date created             :02/26/02
 Time created             :15:19:35
 Record start date        :01/06/2001
 Record start time        :01:00
 Record end date          :27/09/2001
 Record end time          :01:00
 Record time interval :  1 hourly
 Number of records        :       2833
 FILE       : D:\PROGRAMS\IHACRES\TRBNEF1\N2001.SUM

 CONTAINS : Summary of model results.
 Reference Temperature =  20.00
 Version 1.02,  Subperiod=  1,Range=14617 to17449(2833), Subints= 1,Time
 Delay= 1
    f     TauW    %Run     D     Bias     x1      u1   %ARPE    1/c     Tq     Ts     Vs
  1.00    60      9.97
  1.00    60      9.97 .755     .01      .1      .0    .06   341.5   .81   27.28   .458
  1.00    61      9.97
  1.00    61      9.97 .755     .01      .1      .0    .06   343.4   .81   27.26   .458
```

Appendix IV. LULC changes over time by category (area in hectares)

| 1938 \ 1962 | LID | HID | AG | FOR | ACTMIN | ABANMIN | RECMIN | SPOIL | LFIL | *SUM* |
|---|---|---|---|---|---|---|---|---|---|---|
| LID | 64.0 | 0.8 | 18.0 | 24.8 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | *108* |
| HID | 25.2 | 261.1 | 26.5 | 30.1 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | *343* |
| AG | 57.6 | 47.7 | 2998.1 | 2549.2 | 25.3 | 279.1 | 0.0 | 32.4 | 0.0 | *5990* |
| FOR | 12.8 | 1.4 | 556.9 | 11214.4 | 77.3 | 340.5 | 0.0 | 62.2 | 0.0 | *12265* |
| ACTMIN | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | *0.0* |
| ABANMIN | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | *0.0* |
| SPOIL | 0.1 | 1.4 | 3.9 | 42.1 | 0.3 | 0.2 | 0.0 | 22.2 | 0.0 | *70* |
| *SUM* | *160* | *312* | *3603* | *13861* | *103* | *620* | *0* | *117* | *0* | *18776* |

| 1962 \ 1982 | LID | HID | AG | FOR | ACTMIN | ABANMIN | RECMIN | SPOIL | LFIL | *SUM* |
|---|---|---|---|---|---|---|---|---|---|---|
| LID | 87.0 | 18.3 | 12.4 | 39.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | *158* |
| HID | 11.7 | 260.8 | 16.7 | 22.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | *312* |
| AG | 131.4 | 34.5 | 1583.8 | 1283.8 | 165.8 | 12.5 | 387.4 | 5.4 | 0.0 | *3605* |
| FOR | 62.7 | 17.5 | 639.6 | 11619.3 | 371.8 | 78.0 | 1053.8 | 18.1 | 0.0 | *13861* |
| ACTMIN | 0.0 | 0.0 | 1.7 | 48.4 | 11.6 | 7.7 | 33.4 | 0.1 | 0.0 | *103* |
| ABANMIN | 1.1 | 0.0 | 34.9 | 264.1 | 98.1 | 60.9 | 161.6 | 0.0 | 0.0 | *621* |
| SPOIL | 2.4 | 0.1 | 3.9 | 77.1 | 3.8 | 4.8 | 12.3 | 12.6 | 0.0 | *117* |
| *SUM* | *296* | *331* | *2293* | *13355* | *651* | *164* | *1649* | *36* | *0* | *18775* |

| 1982 \ 1997 | LID | HID | AG | FOR | ACTMIN | ABANMIN | RECMIN | SPOIL | LFILL | *SUM* |
|---|---|---|---|---|---|---|---|---|---|---|
| LID | 174.4 | 34.8 | 26.9 | 58.2 | 0.2 | 0.0 | 1.7 | 0.0 | 0.0 | *296* |
| HID | 47.7 | 259.6 | 4.0 | 19.6 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | *331* |
| AG | 70.3 | 45.5 | 1222.3 | 736.6 | 39.6 | 5.0 | 173.3 | 0.4 | 0.0 | *2293* |
| FOR | 170.5 | 63.0 | 397.3 | 11563.4 | 185.6 | 68.0 | 862.7 | 12.5 | 31.2 | *13354* |
| ACTMIN | 0.7 | 0.0 | 33.8 | 140.4 | 75.7 | 1.8 | 398.5 | 0.4 | 0.0 | *651* |
| ABANMIN | 0.3 | 0.0 | 3.5 | 92.1 | 0.0 | 10.6 | 57.1 | 0.3 | 0.0 | *164* |
| RECMIN | 0.3 | 0.1 | 99.0 | 532.4 | 97.9 | 18.0 | 898.6 | 2.1 | 0.0 | *1648* |
| SPOIL | 0.1 | 0.1 | 5.0 | 18.5 | 0.0 | 1.3 | 7.5 | 3.7 | 0.0 | *36* |
| *SUM* | *464* | *403* | *1792* | *13161* | *399* | *105* | *2400* | *19* | *31* | *18774* |

REFERENCES

Allan, J.D., Erickson, D.L., and J. Fay. 1997. The influences of watershed landuse on stream integrity across multiple spatial scales. Freshwater Biol. 37:149-161.

Andreassian, V., Perrin, C., Michel, C., Usart-Sanchez, I., and J. Lavabre. 2001. Impact of imperfect rainfall knowledge on the efficiency and the parameters of watershed models. J. Hydrol. 250 (1-4): 206-223.

Barnhisel, R.I. and J.M. Hower. 1997. Coal surface mine reclamation in the eastern United States: the revegetation of disturbed lands to hayland/pasture or cropland. Advances in Agron. 61:233-275.

Bell, J.C., Cunningham, R.L., and C.T. Anthony. 1994. Morphological characteristics of reconstructed prime farmland soils in western Pennsylvania. J. Environ. Qual. 23:515-520.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resources Research 18:1311-1325.

Bonta, J.V., Amerman, C.R., Dick, W.A., Hall, G.F., Harlukowicz, T.J., Razem, A.C., and N.E. Smeck. 1992. Impact of surface coal mining on three Ohio watersheds-physical conditions and ground-water hydrology. Water Resour. Bull. 28:577-596.

Bonta, J.V., Amerman, C.R., Harlukowicz, and W.A. Dick. 1997. Impact of coal surface mining on three Ohio watersheds-surface water hydrology. J. Amer. Water Resour. Assoc. 33:907-917.

Burges, S.J., M.S. Wigmosta, and J.M. Meena. 1998. Hydrological effects of landuse change in a zero-order watershed. J. Hydrol. Eng. 3:86-97.

Burt, T.P., and W.T. Swank. 1992. Flow frequency responses to hardwood-to-grass conversion and subsequent succession. Hydrological Processes. 6:179-188.

Burton, T.A. 1997. Effects of basin-scale timber harvest on water yield and peak streamflow. J. Amer Water Resour. Assoc. 33:1187-1196.

Bussler, B.H., Byrnes, W.R., and Pope, P.E., and W.R. Chaney. 1984. Properties of minesoil reclaimed for forest landuse. Soil Sci. Soc. Am. J. 48:178-184.

Chapman, T.G. 1996a. Common unitgraphs for sets of runoff events.1. Unitgraph identification from streamflow data. Hydrol. Processes. 10:773-782.

Chapman, T.G. 1996b. Common unitgraphs for sets of runoff events.2.Comparisons and inferences for rainfall loss models. Hydrol. Processes. 10:783-792.

Chong, S.K., and P.T. Cowsert. 1997. Infiltration in reclaimed mined land ameliorated with deep tillage treatments. Soil and Tillage Res. 44:255-264.

Chiew, F.H.S., Stewardson, M.J., and T.A. Mcmahon. 1993. Comparison of 6 rainfall-runoff modeling approaches. J. Hydrol. 147 (1-4): 1-36.

Chow, V. T., Maidment, D. R. and Mays, L. W. Applied Hydrology: McGraw-Hill 1988

Dietrich, C.R. 1996. Linear rainfall-runoff system identification with ramifications for modeling watershed processes. Hydrol Proc. 10:893-902.

Dingman, S.L., 1994. Physical Hydrology. Prentice-Hall, Upper Saddle River.

Dunker, R.E., Hooks, C.L., Vance, S.L., and R.G. Darmody. 1995. Deep tillage effects on compacted surface-mined land. Soil Sci. Soc. Am. J. 59:192-199.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. San Francisco: W.H. Freeman. 818 pp.

Forstall, R.L. 1995. Population of Counties by Decennial Census: 1900 to 1990. Online report: http://www.census.gov/population/cencounts/md190090.txt

Freeze, R.A. 1974. Streamflow generation. Reviews of geophysics and space physics. 124:627-647.

French, M.N., and W.F. Krajewski. 1994. A model for real-time quantititative rainfall forecasting using remote sensing. Water Resour. Res. 30:1075-1083.

Gebert, W.A., and W.R. Krug. 1996. Streamflow trends in Wisconsin's driftless area. Water Resour. Bull. 32:733-744.

Gifford, G.F., Humphries, W., and R.A. Jaynes. 1984. A preliminary quantification of the impacts of aspen to conifer succession on water yield – II. Modeling results. Water Resour. Bull. 20:181-186.

Guebert, M.D. and T.W. Gardner. 2001. Macropore flow on a reclaimed surface mine: infiltration and hillslope hydrology. Geomorphology. 39:151-169.

Hansen, D.P., Ye, W., Jakeman, A.J., Cooke, R., and P. Sharma. 1996. Analysis of the effect of rainfall and streamflow data quality and watershed dynamics on streamflow prediction using the rainfall-runoff model IHACRES. Environ. Softw. 11 (1-3): 193-202.

Hewlett, J.D., and A.R. Hibbert. 1967. Factors affecting the response of small watersheds to precipitation in humid areas, in Proceedings of the International Symposium on Forest Hydrology, pp. 275-290, Pennsylvania State University, University Park.

Hornbeck, J.W., Pierce, R.S., and C.A. Federer. 1970. Streamflow changes after forest clearing in New England. Water Resour. Res. 6:1124-1132.

Hypio, S.J. 2000. Streamwater nitrogen export from the Savage River watershed, westen Maryland. Masters Thesis. University of Maryland, College Park, MD.

Jones, J.A., and G.E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resour. Res. 32:959-974.

Kochenderfer, J.N., Edwards, P.J., and F. Wood. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices. Northern J. Appl. For. 14:207-218.

Kokkonen, T., Koivusalo, H., and T. Karvonen. 2001. A semi-distributed approach to rainfall-runoff modeling – a case study in a snow affected watershed. Environ. Modell. Softw. 16 (5): 481-493.

Kuhnle, R.A., Bingner, R.L., Foster, G.R., and E.H. Grissinger. 1996. Effect of landuse changes on sediment transport in Goodwin Creek. Water Resour. Res. 32:3189-3196.

Langbein, W.B. 1940. Channel storage and unit hydrograph studies; EOS, Amer Geophys. Union Trans. 21:620-627.

Letcher, R.A., Schreider, S.Y., Jakeman, A.J., Neal, B.P., and R.J. Nathan. 2001. Environmetrics. 12 (7): 613-630.

Littlewood, I.G., Down, K., Parker, J.R., and D.A. Post. 1997. IHACRES v1.0 User Guide. Center for Ecology and Hydrology, Wallingford, UK & Integrated Watershed Assessment and Management Centre, Australian National University, Canberra, 97 pp.

Maryland Department of Natural Resources. 2001. Georges Creek Watershed Characterization. (draft). 73pp.

McSweeney, K. and I.J. Jansen. 1984. Soil structure and associated rooting behavior in minesoils. Soil Sci. Soc. Am. J. 48: 607-612

Mwendera, E.J., and M.A. Mohamed-Saleem. 1997. Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in Ethiopian highlands. Soil Use Manag. 13:29-35.

Rantz, S.E. 1971. Suggested criteria for hydrologic design of storm-drainage facilities in the San Francisco Bay Region, California; U.S. Geological Survey Open File Report, Menlo Park, CA.

Ritter, J.B., and T.W. Gardner. 1993. Hydrologic evolution of drainage basins disturbed by surface mining, central Pennsylvania. Geol. Soc. Amer. Bull. 105:101-115.

Rose, S., and N.E. Peters. In press. Effects of urbanization on streamflow in the Atlanta area (George USA): a comparative hydrological approach. Hydrol. Proc.

Schreider, S.Y., Jakeman, A.J., and A.B. Pittock. 1996. Modelling rainfall-runoff from large watershed to basin scale: The Goulburn Valley, Victoria. Hydrol. Proc. 10 (6): 863 –876.

Schreider, S.Y., Young, P.C., and A.J. Jakeman. 2001. An application of the Kalman filtering technique for streamflow forecasting in the Upper Murray Basin. Math. Comput. Model. 33 (6-7): 733-743.

Schueler, T. 1994. The importance of imperviousness. Watershed Prot. Tech. 1 (3): 100-111

Sefton, C.E.M., and D.B. Boorman. 1997. A regional investigation of climate change impacts on UK streamflows. J. Hydrol. 195:26-44.

Sherman, L.K. 1932. Stream-flow from rainfall by the unit-graph method, Eng. News-Rec. 108:501-505.

Smith, J.A., and W.F. Krajewski. 1991. Estimation of the mean field bias of radar rainfall estimates, J. Applied Meteor. 30:397-412.

Smith J.A., Seo, D.J., Baeck, M.L., and M.D. Hudlow. 1996. An intercomparison study of NEXRAD precipitation estimates. Water Resour. Res. 32 (7): 2035-2045.

Snyder, F.F. 1938. Synthetic unit hydrographs; EOS, Amer Geophys Union Trans. 19:447-454.

Swanson, R.H. 1984. Managing lodgepole pine: the species nad its management. Symposium Proceedings, May 8-10, 1984, Spokane, Washington, pp. 305-313.

Swift, L.W., Swank, W.T., Mankin, J.B., Luxmoore, R.J., and R.A. Goldstein. 1975. Simulation of evapotransporation and drainage from mature and clear-cut deciduous forests and young pine plantation. Water Resour. Res. 11:667-673.

Thomas, R.B., and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resour. Res. 34:3393-3403.

Troendle, C.A., and R.M. King. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. J. Hydrol. 90:145-157.

United States Congress. 1977. Surface mining control and reclamation act of 1977. 95$^{th}$ Congress, Public Law 95-87.

United States Department of Agriculture. 2001. Fact Finders for Agriculture. http://www.usda.gov/nass.

United States Environmental Protection Agency. Multi-Resolution Land Characteristics-MRLC Homepage. Revised: Friday, March 30, 2001 13:07:50. http://www.epa.gov/mrlc/.

United States Soil Conservation Service 1972. Hydrology, Section 4, National Engineering handbook, Washington, DC.

United States Soil Conservation Service. 1974a. Soil survey of Allegany County, Maryland. 83pp.

United States Soil Conservation Service. 1974b. Soil survey of Garrett County, Maryland. 83pp.

United States Geological Survey. 1983. Hydrology of area 6, eastern coal province, Maryland, West Virginia, and Pennsylvania. Water Resources Investigations: Open-File Report 83-33.

Whipkey, R.Z. 1965. Subsurface stormflow from forested slopes. Int. Assoc. Sci. Hydrol. Bull. 10 (2):74-85.

Ye, W., Bates, B.C., Viney, N.R., Sivapalan, M., and Jakeman, A.J. 1997. Performance of conceptual rainfall-runoff models in low-yielding ephemeral watersheds. Water Resour. Res. 33 (1): 153-166.

Ye, W., Jakeman, A.J., and P.C. Young. 1998. Identification of improved rainfall-runoff models for an ephemeral low-yielding Australian watershed. Environ. Modell. Softw. 13 (1): 59-74.