ABSTRACT

Title of dissertation:	MINIMAL MODELS OF HUMAN-NATURE INTERACTION
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Over the last two centuries, the Human System went from having a small impact on the Earth System to becoming dominant, because both population and per capita consumption have grown extremely fast, especially since about 1950. We therefore argue that Human System Models must be included into Earth System Models through bidirectional couplings with feedbacks. In particular, population should be modeled endogenously, rather than exogenously as done currently in most Integrated Assessment Models. The growth of the Human System threatens to overwhelm the Carrying Capacity of the Earth System, and may be leading to collapse. Earth Sciences should be involved in the exploration of potential mitigation strategies including education, regulatory policies, and technological advances.

We describe a human population dynamics model developed by adding accumulated wealth and economic inequality to a predator-prey model of humans and nature. The model structure, and simulated scenarios that offer significant implications, are discussed. Four equations describe the evolution of Elites, Commoners, Nature, and Wealth. The model shows Economic Stratification or Ecological Strain can independently lead to collapse, in agreement with the historical record.

The measure “Carrying Capacity” is developed and its estimation is shown to be a practical means for early detection of a collapse. Mechanisms leading to two types of collapses are discussed. The new dynamics of this model can also reproduce the irreversible collapses found in history. Collapse can be avoided, and population can reach a steady state at maximum carrying capacity, if the rate of depletion of nature is reduced to a sustainable level, and if resources are distributed equitably.

Finally we present a Coupled Human-Climate-Water Model (COWA). Policies are introduced as drivers of the model so that the long-term effect of each policy on the system can be seen as we change its level. We have done a case study for the Phoenix AMA Watershed. We show that it is possible to guarantee the freshwater supply and sustain the freshwater sources through a proper set of policy choices.

MINIMAL MODELS OF HUMAN-NATURE INTERACTION

by

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Preface

This dissertation is essentially a collection of three of the papers that I have coauthored in my research on Coupled Human-Earth System Models. One of these papers is published and two are under preparation.

In the first paper, we focus on the importance of Coupling Human System Models and Earth System Models through "bidirectional" feedbacks. We emphasize on including Population as an endogenous variable in the models. Then we present the first generation of our minimal model for the Human And Nature Dynamics (HANDY). This model helps us better understand the underlying feedback processes, and develop the notion of "Carrying Capacity". This concept plays a central role in understanding sustainability of various societies. Generalizing this concept to various systems is discussed in the first paper. Results of the HANDY1 model and study are published in the second paper by Motesharrei et al. [2014b]. And finally, we discuss and show the results from our Coupled Human-Climate-Water Model (COWA), subject of the COWA working paper.

I hope that the presented papers can trigger an increasing interest in adopting multidisciplinary approaches to address various socio-environmental problems. There is a huge void in this area, and therefore, a tremendous potential for novel research that produces actionable science.

To my academic parents,

Jim Yorke and Eugenia Kalnay,

for their continued support during my graduate studies.

Acknowledgments

Acknowledging all the people who have been helpful or influenced my research in one way or another can fill up a volume by itself. I have been fortunate to learn information useful for my research from hundreds of scholars, inside and outside academia. I have also been blessed with dozens of great friends in my non-academic life. All of such interactions have contributed to the success of my projects. Nevertheless, I would like to name a few people who have played an essential role, specifically in the production of the presented material in this dissertation.

I have enormously benefited from a large group of advisors, colleagues, and coauthors. First and foremost, I like to offer my biggest thank you to Eugenia Kalnay. Most of the work in this dissertation was done through endless hours of discussion and numerical experiments Eugenia and I did together. The second biggest thanks goes to Jorge Rivas. Eugenia, Jorge, and I constituted the "HANDY Team", responsible for the HANDY1 paper [Motesharrei et al., 2014b]. We are also the core authors of the other two papers presented in this dissertation.

Then I would like to thank my advisors and coauthors James A. Yorke, Klaus Hubacek, Matthias Ruth, Victor Yakovenko, Fernando Miralles-Wilhelm, Ning Zeng, Margaret Palmer, Jagadish Shukla, Takemasa Miyoshi, Robert Cahalan, and Huan Wu. I endlessly appreciate their kind support and advice with my projects.

And thanks go to my fellow graduate students, Fang Zhao and Cortney Gustafson, my coauthors on the COWA paper. Fang produced the required climate time series, and built the River Routing Module. Cortney was essential in the development of COWA and collection of the tremendous body of data required to train and run the model.

A special thanks goes to Alverda McCoy, the wonderful director of the AMSC office. It was impossible for me to go through several stages of my doctoral programs without her continued help.

I appreciate all the help I received from the staff at multiple departments and centers on and off campus. They include the Math, Physics, and AOSC departments, SESYNC, IPST, School of Public Policy, ESSIC, JGCRI, and CSPAC. I would also like to thank NASA which provided partial funding for this work.

And finally, I like to thank all of my family and friends for their uninterrupted faith in my work.

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List of Abbreviations

AOSC	Department of Atmospheric and Oceanic Science (UMD)
CC	Carrying Capacity
COWA	Coupled Human-Climate-Water Model
CSPAC	Clarice Smith Performing Arts Center
ESSIC	Earth System Science Interdisciplinary Center
HANDY	Human and Nature Dynamics
HANDY1	Generation One of HANDY
ICTP	Abdus Salam International Center for Theoretical Physics
IPST	Institute for Physical Science and Technology (UMD)
JGCRI	Joint Global Change Research Institute
NASA	National Aeronautics and Space Administration
PAMAWR	Phoenix AMA Watershed Region
RRM	River Routing Module
SESYNC	National Socio-Environmental Synthesis Center
UMD	University of Maryland

Chapter 1: Introduction

This chapter gives a brief introduction to the general type of problems that we will consider in this thesis. We start with a description of the issues, then propose a general framework to tackle the problem, and end with a description of the progress until now —presented in the following chapters of this dissertation

1.1 Problem Statement

The first decade of the twenty first century has been characterized by an increased awareness of global challenges for humanity and for our planet. On the human side, our world is facing serious social and economic problems. Increasing social inequality appears to exacerbate existing conditions of poverty, hunger, and unrest in many countries. Rising energy prices have resulted in increased food prices, a major topic of discussion during meetings of world leaders, e.g., the 2008 G8 Summit in Tokyo and the 2012 Rio+20 conference in Brazil. Long lasting droughts in northeast Africa have caused a humanitarian crisis in Somalia; sudden drought conditions in Latin America (most notably Mexico in 2011 and Argentina in 2008-9 and 2012-13) have yielded significant economic impacts due to losses in agricultural productivity. Rapidly growing population and high fertility rates is a major factor behind youth unemployment, which is as high as 30% in some Middle East and African countries. Even the United States and the European Union struggle with record level unemployment and other symptoms of long-lasting financial and economic critical conditions.

Overall, drought, famine, poverty, terrorism, disease, conflict, social unrest, and economic state failure are just a few of these challenges, which we must overcome as regions around the world are constrained by factors such as availability of natural resources, a changing climate and population growth. Over-exploitation of natural resources, mostly non-renewable or very slowly renewable such as water and soil, has become a critical problem. Climate change has increased both the frequency and severity of extreme weather events, including floods, droughts, and storm surges. Many of these challenges and driving factors are often intertwined, and understanding their coupling and dynamics is limited to commonly used cause-effect analyses, which are insufficient. This will continue to be the case until transformative approaches are developed and implemented to positively affect stable and secure social, economic and political environments internationally. This proposal attempts to embody such an approach.

Various governments, research institutes and international organizations have attempted to address several of the above-mentioned challenges over the past decades. However, not only are they not being solved, but many of them have actually worsened. For the most part, approaches in academia and research institutes have been single discipline, i.e., with the focus solely placed on specific branches of science, engineering, economics, or another single aspect of the larger problem. Governments and international organizations, i.e., development banks, think tanks, and NGOs, tend to concentrate on a particular socioeconomic "sector" such as water, energy, agriculture, and biodiversity, often ignoring the connections (resources and constraints) between such sectors. Integrated, multi-disciplinary approaches and innovative methods are needed to tackle these global challenges. Finding solutions for these challenges that are effective and sustainable requires a new paradigm that considers apparent and hidden connections between the natural and human systems.

1.2 Project Framework

We will work within the global Human-Earth System framework we have developed that models the interactive dynamics of the five key sub-systems of the human-nature system: population, climate, water, energy/resources, and food/agriculture. The last three subsystems will include an input/output economic module. This will be done through combining data collection, analysis techniques, modeling, and data assimilation. We will develop, and optimize measures and policies that can be implemented in practice for use in early detection of critical and/or collapsing conditions. We also aim to recognize parameters and externalities (such as inadequate measures or policies) that can play a significant role in occurrence of catastrophes and collapses. By adjusting the values of those parameters found to be influential through numerical experiments and simulations, we will generate short-term and long-term policy recommendations that can keep the system within sustainable development targets (e.g., Millennium Development Goals or OECD targets).

1.3 Progress to Date

We have developed prototype models for the five sub-systems of the Human-Earth System. The population, water, and climate sectors are already programmed and coupled with each other. The Earth System model (UMD-ICTP), developed originally by Ning Zeng and Fred Kucharski, has an interactive dynamical vegetation model (VEGAS), and produces simulations of climate evolution with simulated temperature and precipitation fields that agree well with observations. It also has a coupled River Routing Module (RRM) that, together with the UMD-ICTP GCM, feeds into the Coupled Water model (COWA) through precipitation, evaporation, and river inflow/outflow rates. As a case study, we apply COWA to the Phoenix AMA Watershed.

We have also built a minimal, 4-variable model for conceptual developments and thought experiments, called Human And Nature Dynamics (HANDY) [Motesharrei et al., 2014b]. The variables of HANDY represent "elite" and "commoner" population groups, natural resources, and accumulated wealth. The model develops and defines the concept of "Carrying Capacity", and shows that Carrying Capacity is a practical means for the early estimation of a collapse. HANDY shows how rapid depletion, as well as high inequality in consumption, can each independently lead to a full collapse of the society —similar to those observed many times throughout history. It also shows that Collapse can be avoided, and population can reach a steady state at the maximum carrying capacity, if the rate of depletion of nature is reduced to a sustainable level, and if resources are distributed equitably.

Chapter 2 of this thesis gives a more in-depth description of the existing interactions between the Human System and the Earth System. It then explains the framework proposed above in greater details, and gives a review of the several well-known Human-Earth System models, focusing on the missing bidirectional feedbacks between model components. In particular, an argument is made that the population should be included in the models as an endogenous variable, fully coupled to other sectors of the Human-Earth System. A set of practical solutions is proposed including education, regulatory policies, and technological advancement. Role of the fully-coupled models in evaluating and developing such solutions is discussed. The material presented in chapter 2 is a journal publication that I coauthored with Jorge Rivas, Eugenia Kalnay, Robert Cahalan, Mark Cane, Klaus Hubacek, Fernando Miralles-Wilhelm, Takemasa Miyoshi, Margaret Palmer, Matthias Ruth, Jagadish Shukla, and Victor Yakovenko.

Chapter 3 covers the HANDY1 model: its structure, experiments, and results, all presented in the journal article I coauthored with Jorge Rivas and Eugenia Kalnay.

Chapter 4 covers our Coupled Human-Climate-Water model (COWA). Experiment results for the Phoenix AMA watershed are discussed. The work presented in this chapter is the subject of a working paper I am coauthoring with Cortney Gustafson, Fang Zhao, Jorge Rivas, Huan Wu, Ning Zeng, Fernando Miralles-Wilhelm, and Eugenia Kalnay.

Chapter 2: Population and the Earth System

Over the last two centuries, the Human System has grown from having a small impact on the Earth System to becoming dominant. Both population and per capita consumption have grown extremely fast, especially since about 1950. We argue that the Human System Models must be coupled with the Earth System Models through bidirectional feedbacks. In particular, population should be modeled endogenously, rather than exogenously as in most Integrated Assessment Models. The growth of the Human System threatens to overwhelm the Carrying Capacity of the Earth System, and may be leading to collapse. The Earth Sciences can, and should be, involved in the exploration of mitigation strategies including education, regulatory policies, and technological advances.

2.1 The Dominance of the Human System in the Earth System

Planet Earth has been the habitat of the human population for millions of years. Our life depends on the resources provided to us by the Earth System (ES). We breathe the air from the Earth's atmosphere; we drink the water from rivers, lakes, and wells; we eat the fruits from the trees and the meat and dairy from the animals; over the past 8,000 years we have used the land for agriculture, and we mine the Earth's crust for metals and other minerals. Until about 200 years ago, we used renewable biomass as the major source of energy, but over the course of the past two centuries, we have become heavily dependent on fossil fuels (coal, oil, and natural gas), which made possible both the Industrial Revolution and the Green Revolution. Our relationship with our planet is not limited to consuming its resources. Waste is an inevitable outcome of any production process; what is produced must return to the ES in some form. Trash goes back to the landfills; polluted water goes back to the rivers, streams, lakes, oceans, or into the ground; and greenhouse and other toxic gases go into the atmosphere and the ocean.

Humans thus impact the ES by extracting its resources and by returning waste and pollution back to the system. The level of this impact is determined by the extraction and pollution rates, which in turn, are determined by the total consumption rate. Total consumption equals population multiplied by the average consumption per capita. Using Gross Domestic Product (GDP) per capita as a rough measure of consumption per capita, the extent of the impact of the Human System (HS) on the ES can be estimated from the total population and the average consumption per capita.

World population remained below 5 million for tens of thousands of years. After the Agricultural Revolution, it took the world population 10,000 years to reach *one* billion around 1804. It only took about a century to reach the second billion, around 1922. Then, in less than a century, *five* billion more humans were added [Christenson, 2002]. The peak in the *rate of growth* occurred in the 1960s, but due to the higher population, the peak in *absolute growth* was in the 1990s [Christenson,

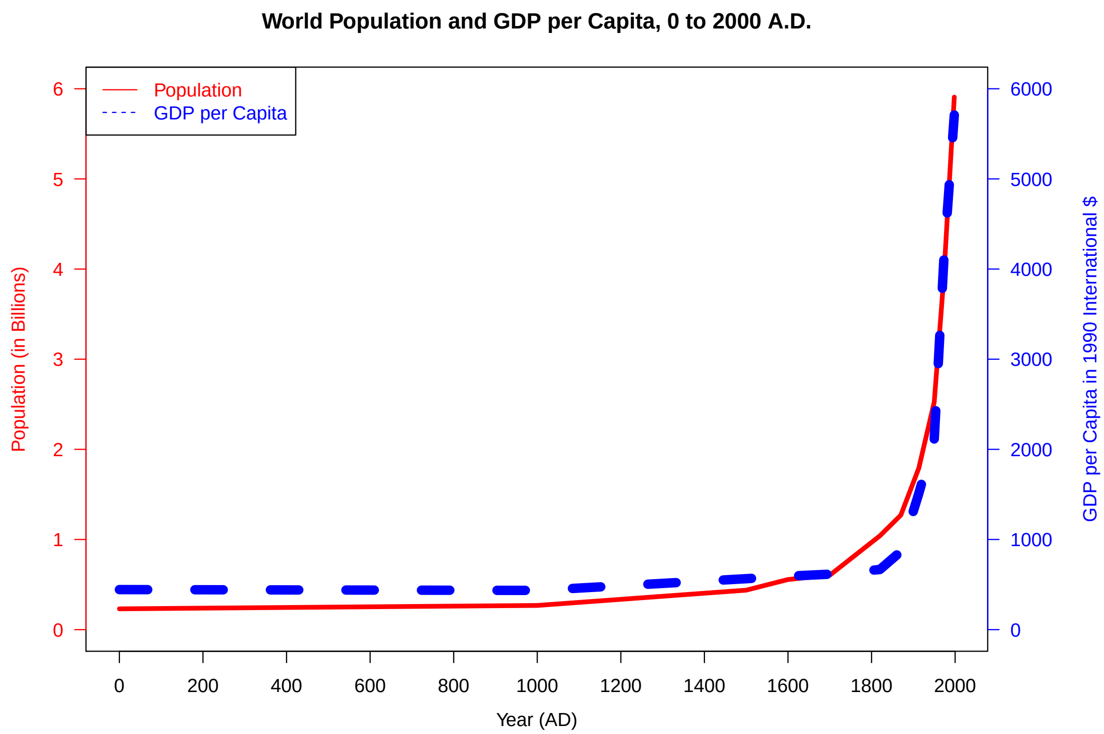

Figure 2.1: From Maddison [2001]

2002]. Even the recent decline in the rate of growth has not significantly reduced the absolute number currently added every year (~75 million, equivalent to the population size of Germany). A similar pattern is true for GDP/capita, with the growth acceleration occurring even more recently (see Fig. 2.1). Thus, until the last century, both population and GDP/capita were so low that the Human System was a negligible component of the Earth System. However, both population and GDP/capita experienced explosive growth after ~1950, and their product —total impact— has grown "super-exponentially" from being almost negligible to becoming dominant in the ES. Despite the widespread belief that population growth is no longer an issue, these trends continue. We are currently adding a billion people every 13–15 years, and are projected to do so for decades to come. Global GDP/capita growth is also not projected to decline significantly.

Two major factors enabled this population explosion. First, advances in sanitation and medicine significantly reduced mortality rates and lengthened average life-span [Dyson, 2010; Preston, 1980]. Second, the efficient and large-scale exploitation of fossil fuels [Krausmann et al., 2009] —a vast stock of nonrenewable resources accumulated by Nature over hundreds of millions of years that we are drawing down in a few centuries— and the invention of the Haber-Bosch process to use natural gas to produce nitrogen fertilizer [Erisman et al., 2008; Smil, 2004], enabled increasingly higher levels of food and energy production, allowing for this fast growing population. For example, between 1950 and 1984, the production of grains increased by 250% due to the use of fossil fuels for fertilization, mechanization, irrigation, and pesticides [Kendall and Pimentel, 1994]. These advances, together with the development of new seed varieties, are referred to as the "Green Revolution" that allowed global population to double in that period [Ramankutty et al., 2002].

The rapidly growing size of the Human System has come to dominate the Earth System in many ways. The majority of the global net primary production (vegetation) is appropriated by Humans[Rojstaczer et al., 2001]. Most cultivatable land is converted to agriculture [Tilman et al., 2002]. Largest portion of large mammals is comprised of domesticated animals [Kareiva et al., 2007; Lyons et al., 2004]. Soils worldwide are eroded, fisheries exhausted, forests denuded, and aquifers drawn down, while desertification due to overgrazing, deforestation, and soil erosion is spreading [Scholes and Scholes, 2013; Vitousek et al., 1997]. Since climate change is expected to make subtropical regions drier, desertification will increase, especially when bidirectional albedo-vegetation feedback is accounted for [Zeng and Yoon, 2009].

At the same time, the outputs of fossil fuel use and land-use changes have become the major drivers of global climate change [Hansen et al., 2013; Tilman et al., 2001]. Atmospheric levels of carbon dioxide, methane, and nitrous oxide not only exceed pre-industrial concentrations by about 40%, 150%, and 20%, respectively, but are now substantially above their maximum ranges of fluctuation over the past 800,000 years, while total carbon dioxide emissions continue to grow at a rapid rate [Ciais et al., 2013]. Arctic sea ice, Antarctic and Greenland ice sheets, global glacier mass, permafrost area, and Northern Hemisphere snow cover are all decreasing substantially, while ocean surface temperatures, sea level, and ocean acidification are rising. The Human System now dominates the global nitrogen cycle, having produced a 20% rise of nitrous oxide (N_2O) in the atmosphere, now the third largest contributor to global warming, and a tripling of ammonia (NH_3) in the atmosphere due to human activities [Galloway et al., 2004]. In total, human processes produce about as much reactive nitrogen as all natural processes combined. Human activities also dominate many regional hydrological cycles [Vrsmarty et al., 2000] to such an extent that major rivers such the Colorado, the Nile, and the Yellow River no longer reach the sea for significant parts of the year. Human processes also play a major role in virtually every major metal's cycle. While the exact causes are difficult to establish, current rates of animal and plant species extinction rates are estimated to be at least 100 times the natural background rate [Regan et al., 2001].

While population has stabilized in some countries, population growth continues to be more than 1% per year in 130 out of about 230 countries in the world [United Nations, 2007]. For example, the United States is projected to grow at a rate of about 1%. With very high consumption and emissions per capita, these developed country population increases have a disproportionate impact. But population growth is not just a problem in the developed countries. One often hears that the continued very high levels of population growth in many of the world's poorest countries is not relevant because they have much lower impact per capita, but it is actually poor populations who have the largest potential to increase their consumption and emissions per capita [Lawrence et al., 2013]. Until the currently wealthy countries can produce a large decline in their emissions per capita, there is no reason to project that the population of the less developed countries will not, in decades to come, be emitting as much per capita as currently wealthy countries do today (China's recent dramatic rise in emissions per capita has confirmed this future path for the developing world). To argue otherwise requires assuming that today's developing countries will remain in desperate poverty.

Herman Daly (one of the founders of the field of Ecological Economics) has pointed out that this path is not sustainable: "We are drawing down the stock of natural capital as if it was infinite" [Daly and Farley, 2003b]. Contrary to standard economic theory, physical laws place real constraints on the way in which materials and energy can be used and discharged in the Human Economy [Georgescu-Roegen, 1971; Ruth, 1993]. To be sustainable, human consumption must remain at or below what can be renewed and processed by the Earth System.

Economic theories that endorse limitless growth are based on a model of the economy that does not account for the resource inputs and waste outputs, i.e., essentially the model of a perpetual motion machine. But in the real world, economic activity both consumes physical material and energy inputs and produces physical waste outputs. The Earth System performs the functions ("ecosystem services") of providing both the *Sources* of these material and energy inputs to the human economy, as well as the *Sinks* which absorb and process the pollution and waste outputs of the human economy. Since the *scale* of the human economy has grown dramatically relative to Earth System's ability to provide these ecosystem services, the problems of *depletion* and *pollution* have grown dramatically [Daly, 1996b].

It is often suggested technology will solve environmental sustainability problems [Nordhaus et al., 1973; Simon, 1981; Solow, 1974]. However, while technological change can increase resource-use efficiency, it also raises the scale of resource extraction and per capita resource consumption, such that, absent policy effects, the increases in consumption associated with the "Rebound Effect" often compensate for the increased efficiency of resource-use [Greening et al., 2000b; Polimeni et al., 2008b; Ruth, 2009b]. Technological advances that appear to be increases in productivity are often due to greater resource throughput, accompanied by greater waste output. Thus, despite tremendous technological advances, resource-use per capita as well as waste and emissions per capita continue to increase. Technological advances could and should be a part of the solutions to environmental and sustainability problems, but these technological solutions will not just happen by themselves; they require policies based on scientific knowledge to guide and support their development and adoption.

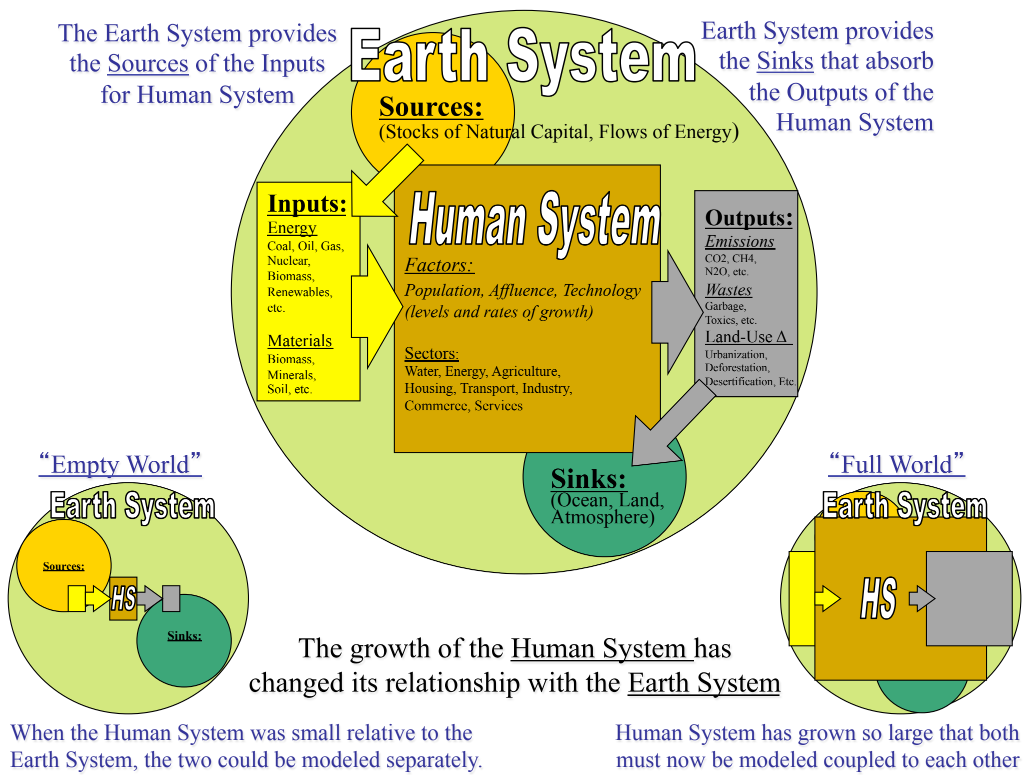

Figure 2.2: Relationship of Human System and Earth System, after Daly and Farley [2003b]. When the human economy was very small relative to the Earth System, it could be modeled alone. The Human System has grown so large relative to the Earth System that both must now be modeled coupled to each other.

Modern society is built on the consumption of the solar capital accumulated over hundreds of millions of years (i.e., fossil fuels) which cannot be replenished on a human timescale [Meyers, 2012]. If we consume these fossil fuels over a few hundred years, we would be using up this capital in one millionth of the time it took to accumulate. Therefore, by definition, modern civilization's energy consumption will not be sustainable until it comes from energy sources other than fossil fuels.

An important concept for the study of sustainability is Carrying Capacity, the population level that the resources of a particular environment can maintain over the long term [Catton, 1980b; Cohen, 1995b; Daly and Farley, 2003b]. A population overshooting the Carrying Capacity is exposed to collapse, as has happened many dozens of times in the last 5000 years. A recent study focusing on the many collapses that took place in Europe has excluded climate forcing, war, and disease as the root cause of such collapses, leading to the conclusion that overrunning Carrying Capacity —the level of population that the ecological system can sustain— has been the root cause of collapses [Shennan et al., 2013b].

In order to study the mechanisms behind such collapses, we built a human population dynamics model, HANDY1 [Motesharrei et al., 2014b], by adding accumulated wealth and economic inequality to a predator-prey model of human-nature interaction. The model shows Economic Stratification and Ecological Strain both play a role in collapse, in agreement with the historical record. Although the Carrying Capacity (CC) is defined mathematically within HANDY1, experiments from HANDY1 show that it can also be estimated empirically as the level of population at the time accumulated wealth starts declining. Experiments presented in the HANDY1 paper for different kinds of societies show that as long as population does not overshoot the Carrying Capacity by too much, it is possible to converge to a sustainable level. However, if the overshoot is too large, a full collapse becomes inevitable. One can generalize the definition of Carrying Capacity (CC) to subsystems with different types of natural resources coupled with population. For example, the subsystems water, energy, and land each coupled bidirectionally to population result in Water CC, Energy CC, and Land CC. Water CC can be defined as the level of population that can be sustained given the level of water sources and supply in the area under study. In general, this level depends on both human and natural factors. For example, Water CC is determined by the natural flow rate of water into and out of the area, precipitation and evaporation, withdrawal rate from water sources, dispensing technology, recycling capacity, etc. Moreover, Water, Energy, or Land CC in a certain area can be improved through imports from other regions [Feng et al., 2011; Rees, 1996; Wrtenberger et al., 2006].

2.2 The Need for Bidirectional Coupling of the Human System and the Earth System Models

In the 1960s atmospheric scientists developed the first mathematical models to understand the dynamics of the Earth's climate, starting with atmospheric models coupled to simple surface models (e.g., Manabe et al. [1965]). In the following decades new components such as land, ocean, sea-ice, clouds, vegetation, carbon, and other chemical constituents were added to make Earth System Models (ESM) more physically complete. These couplings needed to be bidirectional in order to include feedbacks [Manabe et al., 1965].

The importance of accounting for bidirectional feedbacks is shown by the phenomenon of El Niño-Southern Oscillation (ENSO), which results from the coupled dynamics of the ocean-atmosphere subsystem. Until the 1980s, atmospheric and ocean models were coupled in a simple, one-way mode: the atmospheric models were affected by the sea surface temperature (SST) but could not change it, and the ocean models were driven by the atmospheric wind stress and surface heat fluxes, but could not change them. Such unidirectional coupling could not represent the positive, negative, and delayed feedbacks that take place in nature and which produce the ENSO episodes. Cane et al. [1986] developed the first prototype of a bidirectional coupled ocean atmosphere model, and this model for the first time allowed Zebiak and Cane [1987] for the prediction of El Niño several seasons in advance. Most current climate models have since switched to fully coupled atmosphere-ocean-land-ice submodels. This example shows that we can miss very important possible outcomes if the model fails to consider the bidirectional feedbacks between different coupled components of the model. Since the Human System (HS) is currently so dominant, in order to simulate its interaction with the Earth System it is essential to fully couple the the two.

This process has taken place to a certain extent but the coupling does not include bidirectional feedbacks. Energy and Agriculture sectors have been added to ESMs creating "Integrated Assessment Models" (IAMs). There are now several IAMs, including MIT's IGSM, DOE's GCAM, IIASA's MESSAGE, the Netherlands EAA's IMAGE, etc [Bouwman et al., 2006; Calvin et al., 2013; Edmonds et al., 1994; Nakicenovic and Riahi, 1990; Prinn et al., 1999; Sokolov et al., 2005]. In order to estimate the future demand in the IAMs, population information is usually obtained from a demographic projection like the United Nations Population Data. These tables of estimated population determine the changes in resource and pollution/emission levels, which in turn can determine other variables such as atmospheric temperature. However, the changes in resource levels, pollution, temperature, precipitation, etc estimated by the IAMs cannot in turn impact the level of population because the model population is estimated independently of the IAMs. In other words, there is no feedback onto population, so that the coupling between population and ES in most current IAMs is unidirectional , whereas in reality, this coupling is bidirectional.

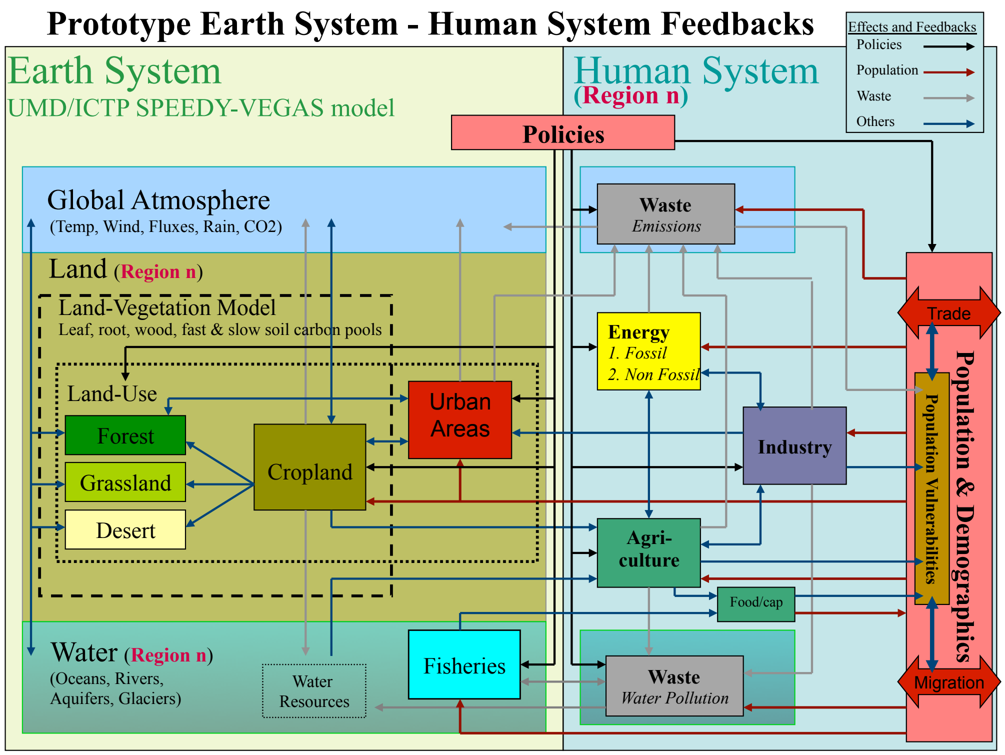

Figure 2.3: Prototype schematic of our proposed Human-Earth System Model

To address the above issues, we propose a global Human-Earth System framework (see Fig. 2.3) that models the interactive dynamics of the key subsystems of the human-nature system: population, climate, water, energy/resources, and food/agriculture. The last three subsystems include an input/output economic module. This should be done through combining data collection, analysis techniques, modeling, and data assimilation. This framework allows developing and optimizing measures and policies that can be implemented in practice for use in early detection of critical and/or collapsing conditions. Moreover, parameters and externalities (such as inadequate measures or policies) that may play a significant role in occurrence of catastrophes and collapses can be detected. By adjusting the values of those parameters found to be influential through numerical experiments and simulations, short-term and long-term policy recommendations that can keep the system within sustainable development targets (e.g., Millennium Development Goals or OECD targets) can be designed and tested.

The policies to be modeled should include government policies that have been proven to be successful. For example the province of Misiones, Argentina, whose protection of the forest maximizes both the local vegetation and the income of the population, stands out in satellite measurements of leaf density [Izquierdo et al., 2008]. The state of Kerala, India, despite a GDP per capita of just $300, through access to education and medical care, enjoys higher life expectancy, lower birth rate, and superior education compared to the rest of India [Jeffrey, 1992; Thamaramangalam, 1998]. Education itself can be rendered in different forms. Education through mass media can be influential for changing long-term cultural trends and social norms, as can be seen, for example, from the impact of soap operas on fertility rates in Brazil [La Ferrara et al., 2012]. Formal education in K–12 and College can reduce societal inequalities and improve economic productivity [Lutz and Samir, 2011]. There are also extremely successful non-coercive population policies, e.g., in Thailand, Mexico, and Iran [Potts, 1997; Potts and Marsh, 2010; Pritchett, 1994; Wikipedia, 2014]. A study by Wire [2009] shows family planning is four times as efficient as adopting low carbon technologies in reducing carbon in the atmosphere and ocean. Efficient policies are also needed for the other four sectors of the human-earth system described above. A dynamical model of such system should be capable of testing the effects of various policy choices on the long-term sustainability of the system. We have developed prototype models for the five subsystems of the Human-Earth System. The population, water, and climate sectors are already programmed and coupled with each other. The Earth System model (UMD-ICTP) has an interactive dynamical vegetation model (VEGAS), and produces simulations of climate evolution with simulated temperature and precipitation fields that agree fairly well with observations [Kucharski et al., 2013]. It also has a coupled River Routing Module (RRM) that, together with the UMD-ICTP GCM, feeds into the Coupled Water model (COWA) through precipitation, evaporation, and river inflow/outflow rates [Motesharrei et al., 2014a]. Data assimilation techniques such as the Local Ensemble Transform Kalman Filter [Hunt et al., 2007] can be efficiently employed to tune the models to fit past data. The importance and imminence of sustainability problems at local and global scales and the key role that the Earth System plays calls for a strong involvement of Earth Scientists in corresponding studies. To be successful, such works require collaborations across disciplines that aim to synthesize knowledge, models, methods, and data. We will need appropriate *mitigating policies*, *education* that raises collective awareness, and investment in building new and improving existing *technologies* to combat potential socio-environmental challenges. It would be only through well-informed decisions that we can leave a planet for future generations in which they can prosper.

Chapter 3: Human and Nature Dynamics (HANDY): Modeling Inequality and Use of Resources in the Collapse or Sustainability of Societies

There are widespread concerns that current trends in resource-use are unsustainable, but possibilities of overshoot/collapse remain controversial. Collapses have occurred frequently in history, often followed by centuries of economic, intellectual, and population decline. Many different natural and social phenomena have been invoked to explain specific collapses, but a general explanation remains elusive.

In this paper, we build a human population dynamics model by adding accumulated wealth and economic inequality to a predator-prey model of humans and nature. The model structure, and simulated scenarios that offer significant implications, are explained. Four equations describe the evolution of Elites, Commoners, Nature, and Wealth. The model shows Economic Stratification or Ecological Strain can independently lead to collapse, in agreement with the historical record.

The measure "Carrying Capacity" is developed and its estimation is shown to be a practical means for early detection of a collapse. Mechanisms leading to two types of collapses are discussed. The new dynamics of this model can also reproduce the irreversible collapses found in history. Collapse can be avoided, and population can reach a steady state at maximum carrying capacity if the rate of depletion of nature is reduced to a sustainable level and if resources are distributed equitably.

3.1 Introduction

There are widespread concerns that current trends in population and resource-use are unsustainable, but the possibilities of an overshoot and collapse remain unclear and controversial. How real is the possibility of a societal collapse? Can complex, advanced civilizations really collapse? It is common to portray human history as a relentless and inevitable trend toward greater levels of social complexity, political organization, and economic specialization, with the development of more complex and capable technologies supporting ever-growing population, all sustained by the mobilization of ever-increasing quantities of material, energy, and information. Yet this is not inevitable. In fact, cases where this seemingly near-universal, long-term trend has been severely disrupted by a precipitous collapse —often lasting centuries— have been quite common. A brief review of some examples of collapses suggests that the process of rise-and-collapse is actually a recurrent cycle found throughout history, making it important to establish a general explanation of this process [Chase-Dunn and Hall, 1997; Goldstein, 1988; Meadows et al., 1972; Modelski, 1987; Tainter, 1988; Turchin and Nefedov, 2009; Yoffee and Cowgill, 1988].

The Roman Empire's dramatic collapse (followed by many centuries of population decline, economic deterioration, intellectual regression, and the disappearance of literacy) is well known, but it was not the first rise-and-collapse cycle in Europe. Prior to the rise of Classical Greco-Roman civilization, both the Minoan and Mycenaean Civilizations had each risen, reached very advanced levels of civilization, and then collapsed virtually completely [Morris, 2006; Redman, 1999]. The history of Mesopotamia —the very cradle of civilization, agriculture, complex society, and urban life— presents a series of rise-and-declines including the Sumerians, the Akkadian, Assyrian, Babylonian, Achaemenid, Seleucid, Parthian, Sassanid, Umayyad, and Abbasid Empires [Redman et al., 2004; Yoffee, 1979]. In neighboring Egypt, this cycle also appeared repeatedly. In both Anatolia and in the Indus Valley, the very large and long-lasting Hittite and Harrapan civilizations both collapsed so completely that their very existence was unknown until modern archeology rediscovered them. Similar cycles of rise and collapse occurred repeatedly in India, most notably with the Mauryan and the Gupta Empires [Edwards et al., 1971, 1973; Jansen et al., 1991; Kenoyer, 1998; Thapar, 2004]. Southeast Asia similarly experienced "multiple and overlapping histories of collapse and regeneration" over 15 centuries, culminating in the Khmer Empire based in Angkor, which itself was depopulated and swallowed by the forest during the 15th Century [Stark, 2006]. Chinese history is, very much like Egypt's, full of repeated cycles of rises and collapses, with each of the Zhou, Han, Tang, and Song Empires followed by a very serious collapse of political authority and socioeconomic progress [Chu and Lee, 1994; Lee, 1931; Needham and Wang, 1956].

Collapses are not restricted to the "Old World". The collapse of Maya Civilization is well known and evokes widespread fascination, both because of the advanced nature of Mayan society and because of the depth of the collapse [Demerest et al., 2004; Webster, 2002]. As Diamond [2005] puts it, it is difficult to ignore "the disappearance of between 90 and 99% of the Maya population after A.D. 800 ... and the disappearance of kings, Long Count calendars, and other complex political and cultural institutions." In the nearby central highlands of Mexico, a number of powerful states also rose to high levels of power and prosperity and then rapidly collapsed, Teotihuacan (the sixth largest city in the world in the 7th C) and Monte Alban being just the largest of these to experience dramatic collapse, with their populations declining to about 20-25% of their peak within just a few generations [Tainter, 1988].

We know of many other collapses including Mississippian Cultures such as Cahokia, South West US cultures such as the Pueblo and Hohokam, Andean civilizations such as Tiwanaku, Sub-Saharan civilizations such as Great Zimbabwe, and many collapses across the Pacific Islands, such as Easter Island. It is also likely other collapses have also occurred in societies that were not at a sufficient level of complexity to produce written records or archeological evidence. Indeed, a recent study [Shennan et al., 2013a] of the Neolithic period in Europe has shown that "in contrast to the steady population growth usually assumed, the introduction of agriculture into Europe was followed by a boom-and-bust pattern in the density of regional populations". Furthermore "most regions show more than one boom-bust pattern", and in most regions, population declines "of the order of the 30–60%" can be found. The authors also argue that, rather than climate change or diseases, the timing and evidence point to endogenous causes for these collapses in 19 out of 23 cases studied, suggesting the possibility of "rapid population growth driven by farming to unsustainable levels". Moreover, through wavelet analysis of the archeological data, S. Downey [personal communication] has shown that the average length of such boom-and-bust cycles is about 300–500 years.

In summary, despite the common impression that societal collapse is rare, or even largely fictional, the "picture that emerges is of a process recurrent in history, and global in its distribution" [Tainter, 1988]. See also Goldstein [1988]; Ibn Khaldun [1958]; Kondratieff [1984]; Parsons [1991]; Yoffee and Cowgill [1988]. As Turchin and Nefedov [2009] contend, there is a great deal of support for "the hypothesis that secular cycles — demographic-social-political oscillations of a very long period (centuries long) are the rule, rather than an exception in the large agrarian states and empires."

This brings up the question of whether modern civilization is similarly susceptible. It may seem reasonable to believe that modern civilization, armed with its greater technological capacity, scientific knowledge, and energy resources, will be able to survive and endure whatever crises historical societies succumbed to. But the brief overview of collapses demonstrates not only the ubiquity of the phenomenon, but also the extent to which advanced, complex, and powerful societies are susceptible to collapse. The fall of the Roman Empire, and the equally (if not more) advanced Han, Mauryan, and Gupta Empires, as well as so many advanced Mesopotamian Empires, are all testimony to the fact that advanced, sophisticated, complex, and creative civilizations can be both fragile and impermanent.

A large number of explanations have been proposed for each specific case of collapse, including one or more of the following: volcanoes, earthquakes, droughts, floods, changes in the courses of rivers, soil degradation (erosion, exhaustion, salinization, etc), deforestation, climate change, tribal migrations, foreign invasions, changes in technology (such as the introduction of ironworking), changes in the methods or weapons of warfare (such as the introduction of horse cavalry, armored infantry, or long swords), changes in trade patterns, depletion of particular mineral resources (e.g., silver mines), cultural decline and social decadence, popular uprisings, and civil wars. However, these explanations are specific to each particular case of collapse rather than general. Moreover, even for the specific case where the explanation applies, the society in question usually had already experienced the phenomenon identified as the cause without collapsing. For example, the Minoan society had repeatedly experienced earthquakes that destroyed palaces, and they simply rebuilt them more splendidly than before. Indeed, many societies experience droughts, floods, volcanoes, soil erosion, and deforestation with no major social disruption [Tainter, 1988].

The same applies to migrations, invasions, and civil wars. The Roman, Han, Assyrian, and Mauryan Empires were, for centuries, completely militarily hegemonic, successfully defeating the neighboring "barbarian" peoples who eventually did overrun them. So external military pressure alone hardly constitutes an explanation for their collapses. With both natural disasters and external threats, identifying a specific cause compels one to ask, "yes, but why did this particular instance of this factor produce the collapse?" Other processes must be involved, and, in fact, the political, economic, ecological, and technological conditions under which civilizations have collapsed have varied widely. Individual collapses may have involved an array of specific factors, with particular triggers, but a general explanation remains elusive. Individual explanations may seem appropriate in their particular case, but the very universal nature of the phenomenon implies a mechanism that is not specific to a particular time period of human history, nor a particular culture, technology, or natural disaster [Tainter, 1988; Turchin, 2003; Yoffee and Cowgill, 1988].

In this paper we attempt to model collapse mathematically in a more general way. We propose a simple model, not intended to describe actual individual cases, but rather to provide a general framework that allows carrying out "thought experiments" for the phenomenon of collapse and to test changes that would avoid it. This model (called HANDY, for Human and Nature DYnamics) advances beyond existing biological dynamic population models by simultaneously modeling two separate important features which seem to appear across societies that have collapsed: (1) the stretching of resources due to the strain placed on the ecological carrying capacity [Abel, 1980; Catton, 1980a; Kammen, 1994; Ladurie, 1987; Ponting, 1991; Postan, 1966; Redman, 1999; Redman et al., 2004; Wood, 1998; Wright, 2004], and (2) the economic stratification of society into Elites and Masses (or "Commoners") [Brenner, 1985; Diamond, 2005; Goldstone, 1991; Ibn Khaldun, 1958; Parsons, 1991; Turchin, 2005, 2006; Turchin and Nefedov, 2009]. In many of these historical cases, we have direct evidence of Ecological Strain and Economic Stratification playing a central role in the character or in the process of the collapse [Culbert, 1973; Diamond, 2005; Goldstone, 1991; Lentz, 2000; Mitchell, 1990]. For these empirical reasons, and the theoretical ones explained in section 3, our model incorporates both of these two features. Although similar to the Brander and Taylor [1998] model (hereafter referred to as “BT”) in that HANDY is based on the classical predator-prey model, the inclusion of two societal classes introduces a much richer set of dynamical solutions, including cycles of societal and ecological collapse, as well as the possibility of smoothly reaching equilibrium (the ecological carrying capacity). We use Carrying Capacity in its biological definition: the population level that the resources of a particular environment can sustain over the long term [Catton, 1980a; Cohen, 1995a; Daly and Farley, 2003a]. In this paper, we call these environment resources “Nature”.

The paper is organized as follows: section 3.2 gives a brief review of the Predator-Prey model; section 3.3 includes the mathematical description of HANDY; section 3.4 covers a theoretical analysis of the model equilibrium and possible solutions; section 3.5 presents examples of scenarios within three distinct types of societies; section 3.6 gives an overall discussion of the scenarios from section 3.5; and section 3.7 offers a short summary of the paper and a discussion of future work.

3.2 Predator-Prey Model

The Predator-Prey model, the original inspiration behind HANDY, was derived independently by two mathematicians, Alfred Lotka and Vitto Volterra, in the early 20th century [Lotka, 1925; Volterra, 1926]. This model describes the dynamics of competition between two species, say, wolves and rabbits. The governing system of equations is

$$\begin{cases} \dot{x} = (ay)x - bx \\ \dot{y} = cy - (dx)y \end{cases} \tag{3.1}$$

In the above system, x represents the predator (wolf) population; y represents the prey (rabbit) population; a determines the predator's birth rate, i.e., the faster growth of wolf population due to availability of rabbits; b is the predator's death rate; c is the prey's birth rate; d determines the predation rate, i.e., the rate at which rabbits are hunted by wolves.

Rather than reaching a stable equilibrium, the predator and prey populations show periodic, out-of-phase variations about the equilibrium values

$$\begin{cases} x_e = c/d \\ y_e = b/a \end{cases} \tag{3.2}$$

Note consistency of the units on the left and right hand sides of (3.1) and (3.2). A typical solution of the predator-prey system can be seen in figure 3.1.

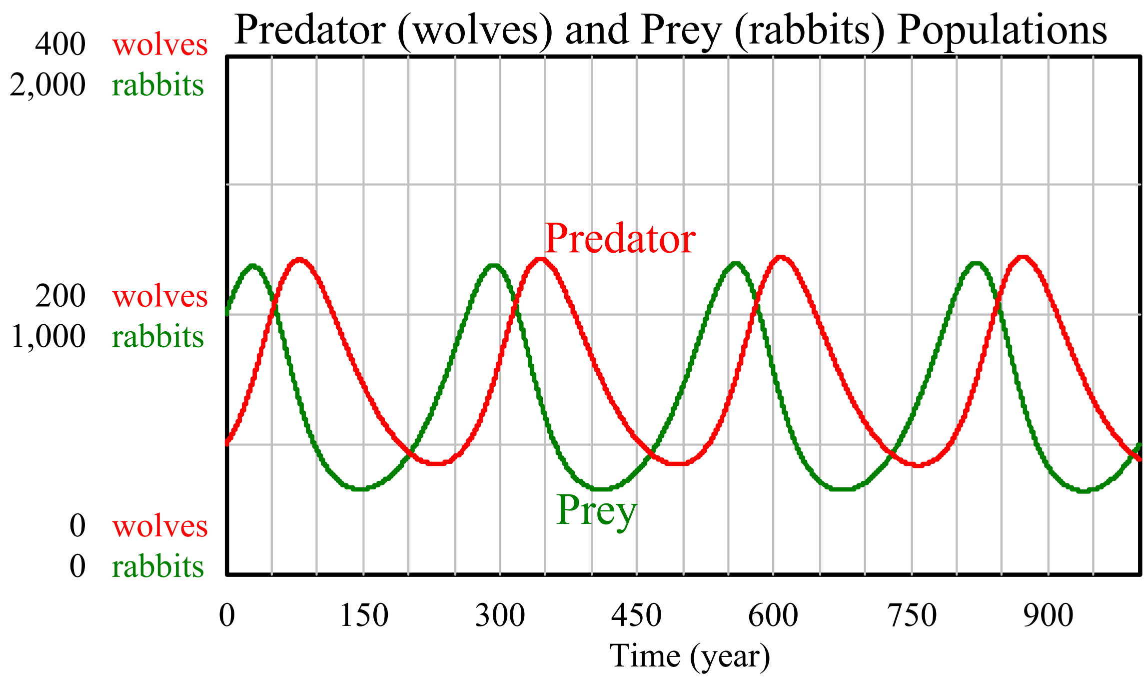

Figure 3.1: A typical solution of the predator-prey system (see equation (3.1))

This typical solution can be obtained by running the system with the following parameter values and initial conditions:

$$\begin{cases} a = 3.0 \times 10^{-5}\ (\text{rabbits.years})^{-1} & b = 2.0 \times 10^{-2}\ \text{years}^{-1} \\ c = 3.0 \times 10^{-2}\ \text{years}^{-1} & d = 2.0 \times 10^{-4}\ (\text{wolves.years})^{-1} \\ x(0) = 1.0 \times 10^{+2}\ \text{wolves} & y(0) = 1.0 \times 10^{+3}\ \text{rabbits} \end{cases} \tag{3.3}$$

Predator population is measured in units of *wolves*, Prey population is measured in units of *rabbits*, and Time is measured in units of *years*.

3.3 HANDY

As indicated above, Human And Nature DYnamics (HANDY) was originally built based on the predator-prey model. We can think of the human population as the "predator", while nature (the natural resources of the surrounding environment) can be taken as the "prey", depleted by humans. In animal models, carrying capacity is an upper ceiling on long-term population. When the population surpasses the carrying capacity, mechanisms such as starvation or migration bring the population back down. However, in the context of human societies, the population does not necessarily begin to decline upon passing the threshold of carrying capacity, because, unlike animals, humans can accumulate large surpluses (i.e., wealth) and then draw down those resources when production can no longer meet the needs of consumption. This introduces a different kind of delay that allows for much more complex dynamics, fundamentally altering the behavior and output of the model. Thus, our model adds the element of accumulated surplus not required in animal models, but which we feel is necessary for human models. We call this accumulated surplus "wealth".

Empirically, however, this accumulated surplus is not evenly distributed throughout society, but rather has been controlled by an elite. The mass of the population, while producing the wealth, is only allocated a small portion of it by elites, usually at or just above subsistence levels. Based on this, and on the historical cases discussed in the introduction, we separated the population into "Elites" and "Commoners", and introduced a variable for accumulated wealth. For an analysis of this two-class structure of modern society, see Banerjee and Yakovenko [2010]; Drăgulescu and Yakovenko [2001]. This adds a a different dimension of predation whereby Elites "prey" on the production of wealth by Commoners. As a result, HANDY consists of four prediction equations: two for the two classes of population, Elites and Commoners, denoted by x_E and x_C, respectively; one for the natural resources or Nature, y; and one for the accumulated Wealth, w, referred to hereafter as "Wealth". This minimal set of four equations seems to capture essential features of the human-nature interaction and is capable of producing major potential scenarios of collapse or transition to steady state.

A similar model of population and renewable resource dynamics based on the predator-prey model was developed in the pioneering work of Brander and Taylor [1998] demonstrating that reasonable parameter values can produce cyclical "feast and famine" patterns of population and resources. Their model showed that a system with a slow-growing resource base will exhibit overshooting and collapse, whereas a more rapidly growing resource base will produce an adjustment of population and resources toward equilibrium values. They then applied this model to the historical case of Easter Island, finding that the model provides a plausible explanation of the population dynamics known about Easter Island from the archeological and scientific record. They thus argue that the Polynesian cases where population did collapse were due to smaller maximum resource bases (which they call "carrying capacity") that grew more slowly, whereas those cases which did not experience such a collapse were due to having a larger resource base (i.e., a larger carrying capacity). They then speculate that their model might be consistent with other historical cases of collapse, such as the ancient Mesopotamian and Maya civilizations or modern Rwanda.

However, the BT approach only models Population and Nature and does not include a central component of these historical cases: economic stratification and the accumulation of wealth. Thus, despite clear evidence for a stratified class structure in Easter Island's history prior to the collapse (as well as for Mesopotamia, the ancient Maya, and modern Rwanda), the BT model does not include class stratification as a factor. In their model, society produces and consumes as a single homogeneous unit. We feel that a historically realistic modeling of the evolution of human-nature dynamics in these stratified complex societies cannot be achieved without including this class stratification in the model. Brander and Taylor recognize that their model is simple, and that application to more complex scenarios may require further development of the structure of the model. We have found that including economic stratification, in the form of the introduction of Elites and Commoners, as well as accumulated Wealth, results in a much richer variety of solutions, which may have a wider application across different types of societies. HANDY's structure also allows for "irreversible" collapses, without the need to introduce an explicit critical depensation mechanism into the model as other models need to do. Thus while the Brander-Taylor model has only two equations, HANDY has four equations to predict the evolution of the rich and poor populations (Elites and Commoners), Nature, and accumulated Wealth. (We examine other differences in section 3.6.4 of the paper.) The HANDY equations are given by:

$$
\begin{cases}
\dot{x}_C &= \beta_C x_C - \alpha_C x_C \\
\dot{x}_E &= \beta_E x_E - \alpha_E x_E \\
\dot{y} &= \gamma y(\lambda - y) - \delta x_C y \\
\dot{w} &= \delta x_C y - C_C - C_E
\end{cases}
\tag{3.4}
$$

It is to be noted that α_C, α_E, C_C, and C_E are all functions of w, x_C, and x_E. See equations (3.5) and (3.7) and figures 3.2 and 3.3.

3.3.1 Model Description

The total population is divided between the two variables, x_C and x_E, representing the population of commoners and of elites. The population grows through a birth rate β and decreases through a death rate α. β is assumed to be constant for both Elites and Commoners but α depends on Wealth as explained below.

In reality, natural resources exist in three forms: nonrenewable stocks (fossil fuels, mineral deposits, etc), regenerating stocks (forests, soils, animal herds, wild fish stocks, game animals, aquifers, etc), and renewable flows (wind, solar radiation, precipitation, rivers, etc). Future generations of the model will disaggregate these forms. We have adopted a single formulation intended to represent an amalgamation of the three forms, allowing for a clear understanding of the role that natural resources play in collapse or sustainability of human societies.

Thus, the equation for Nature includes a regeneration term, $\gamma y(\lambda - y)$, and a depletion term, $-\delta x_C y$. The regeneration term has been written in the form of a logistic equation, with a regeneration factor, γ, exponential regrowth for low values of y, and saturation when y approaches λ, Nature's capacity — maximum size of Nature in absence of depletion. As a result, the maximum rate of regeneration takes place when $y = \lambda/2$. Production is understood according to the standard Ecological Economics formulations as involving both inputs from, and outputs to, Nature (i.e., *depletion* of natural sources and *pollution* of natural sinks) [Daly, 1996a; Daly and Farley, 2003a]. This first generation of HANDY models the *depletion* side of the equation as if it includes the reduction in Nature due to *pollution*.

The depletion term includes a rate of depletion per worker, δ, and is proportional to both Nature and the number of workers. However, the economic activity of Elites is modeled to represent executive, management, and supervisory functions, but not engagement in the direct extraction of resources, which is done by Commoners. Thus, only Commoners produce.

It is frequently claimed that *technological change* can reduce resource depletion and therefore increase carrying capacity. However, the effects of technological change on resource use are not unidirectional. Technological change can raise the efficiency of resource use, but it also tends to raise both per capita resource consumption and the scale of resource extraction, so that, absent policy effects, the increases in consumption often compensate for the increased efficiency of resource use. These are associated with the phenomena referred to as the Jevons Paradox, and the "Rebound Effect" [Greening et al., 2000a; Polimeni et al., 2008a; Ruth, 2009a]. For example, an increase in vehicle fuel efficiency tends to enable increased per capita vehicle miles driven, heavier cars, and higher average speeds, which then negate the gains from the increased fuel-efficiency. In addition, technological advances can enable greater resource extraction and throughput, which then appears as increases in the productivity of other factors of production. As Daly points out, much of the increase in productivity in both agriculture and industry in the last two centuries has actually come from increased (rather than decreased) resource throughput [Daly, 1991]. A decline in the price of a resource is usually thought to reflect an increase in the abundance of that resource, but in fact, it often reflects that the resource is simply being extracted more rapidly. Rather than extend carrying capacity, this reduces it. Over the long-term, per capita resource-use has tended to rise over time despite dramatic technological advances in resource efficiency. Thus, the sign and magnitude of the effect of technological change on resource use varies and the overall effect is difficult to predict. Therefore, in this generation of HANDY, we assume that the effects of these trends cancel each other out. The model will be developed further to allow the rates of these technology-induced trends to be adjusted in either direction.

Finally, there is an equation for accumulated Wealth, which increases with production, $\delta x_C y$, and decreases with the consumption of the Elites and the Commoners, C_C and C_E, respectively. The consumption of the Commoners (as long as there is enough wealth to pay them) is $s x_C$, a subsistence salary per capita, s, multiplied by the working population. The Elites pay themselves a salary κ times larger, so that the consumption of the Elites is $\kappa s x_E$. However, when the wealth becomes too small to pay for this consumption, i.e., when $w < w_{th}$, the payment is reduced and eventually stopped, and famine takes place, with a much higher rate of death. κ is meant to represent here the factors that determine the division of the output of the total production of society between elites and masses, such as the balance of class power between elites and masses, and the capacity of each group to organize and pursue their economic interests. We recognize the inherent limitations, in this initial generation of our model, of holding that balance (κ) constant in each scenario, but we expect to develop κ further in later generations of HANDY so that it can be endogenously determined by other factors in the model.

C_C and C_E, the consumption rates for the Commoner and the Elite respectively, are given by the following equations:

$$\begin{cases} C_C = \min\left(1, \frac{w}{w_{th}}\right) s x_C \\ \\ C_E = \min\left(1, \frac{w}{w_{th}}\right) \kappa s x_E \end{cases} \tag{3.5}$$

Wealth threshold, w_{th}, is a threshold value for wealth below which famine starts. It depends on the "minimum required consumption per capita", ρ:

$$w_{th} = \rho x_C + \kappa \rho x_E. \tag{3.6}$$

Even when Commoners start experiencing famine, i.e., when $w \leq w_{th}$, the Elites continue consuming unequally as indicated by the factor κ in the second term on the right hand side of (3.6). A graphical representation of the consumption rates are given in figure 3.2.

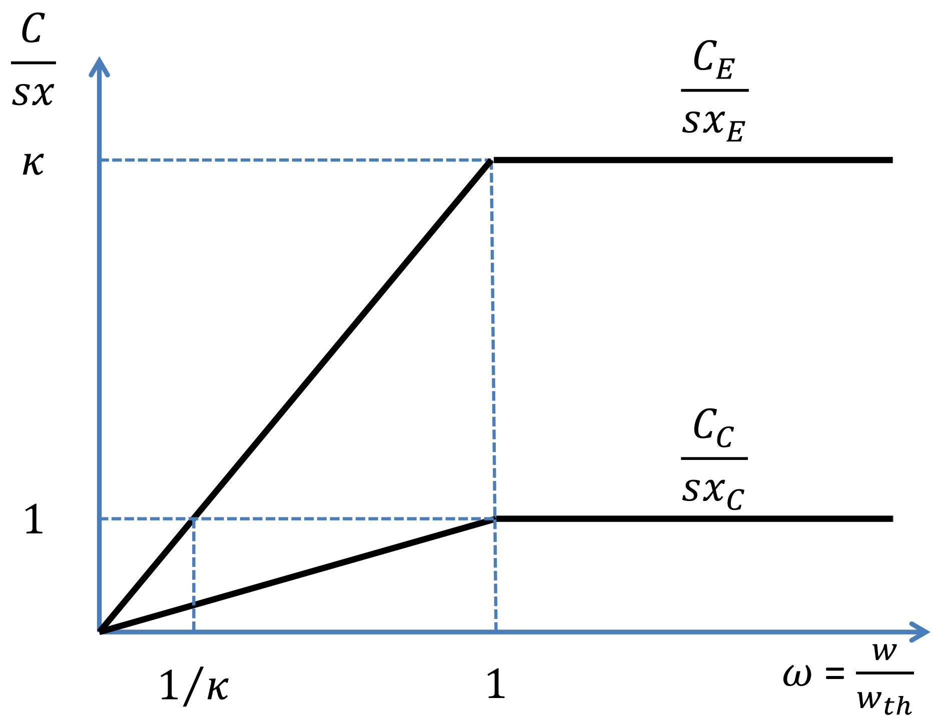

Figure 3.2: Consumption rates for Elites and Commoners as a function of Wealth. Famine starts when $\frac{C}{sx} \leq 1$. Therefore, Commoners start experiencing famine when $\frac{w}{w_{th}} \leq 1$, while Elites do not experience famine until $\frac{w}{w_{th}} \leq \frac{1}{\kappa}$.

The death rates for the Commoner and the Elite, α_C and α_E, are functions of consumption rates:

$$\begin{cases} \alpha_C = \alpha_m + \max\left(0, 1 - \frac{C_C}{sx_C}\right)(\alpha_M - \alpha_m) \\ \alpha_E = \alpha_m + \max\left(0, 1 - \frac{C_E}{sx_E}\right)(\alpha_M - \alpha_m) \end{cases} \tag{3.7}$$

The death rates vary between a normal (healthy) value, α_m, observed when there is enough food for subsistence, and a maximum (famine) value, α_M that prevails when the accumulated wealth has been used up and the population starves. There are a variety of mechanisms which can reduce population when it exceeds carrying capacity, including everything from emigration, increased disease susceptibility, and outright starvation to breakdowns in social order and increased social violence, such as banditry, riots, rebellions, revolutions, and wars. These mechanisms are described in detail in Turchin [2003] but the net effect of all of them is a reduction in population, and that is what the dynamics of our model is meant to represent when we say "population decline" or "famine". Note also that an increase in the death rates (α) is equivalent to an equal decrease in the birth rates (β). The death rates α_C and α_E can be expressed in terms of $\frac{w}{w_{th}}$, a graphical representation of which is given in figure 3.3.

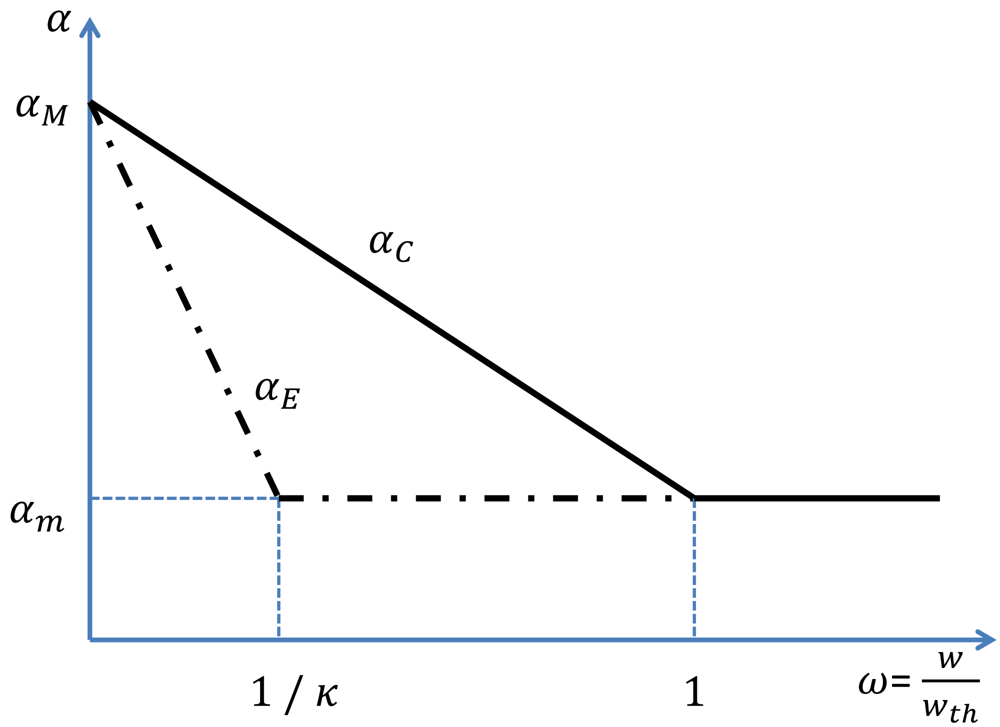

Figure 3.3: Death rates for Elites and Commoners as a function of Wealth. Elites experience famine with a delay due to their unequal access to Wealth.

3.3.2 A Note on Units and Dimensions

There are three dimensions for quantities in HANDY:

1. Population (either Commoner or Elite), in units of *people*.
2. Nature/Wealth, in units of *"eco-Dollars"*.
3. Time, in units of *years*.

The structure of the model requires Nature and Wealth to be measured with the same units, therefore we created the unit *eco-dollar*. Other parameters and functions in the model carry units that are compatible with the abovementioned dimensions following (3.4). For example, Carrying Capacity, χ, and the Maximum Carrying Capacity, χ_M, defined in section 3.4.1, are both expressed in units of *people*.

3.4 Equilibrium Values and Carrying Capacity

We can use the model to find a sustainable equilibrium and maximum carrying capacity in different types of societies. In order for population to reach an equilibrium, we must have $\alpha_m \leq \beta_E \leq \beta_C \leq \alpha_M$. We define a dimensionless parameter, η:

$$\eta = \frac{\alpha_M - \beta_C}{\alpha_M - \alpha_m} \tag{3.8}$$

Since we assume $\alpha_m \leq \beta_C \leq \alpha_M$, η will always be bounded by $0 \leq \eta \leq 1$.

3.4.1 Equilibrium when $x_E = 0$ (No Elites): Egalitarian Society

Assuming $x_E \equiv 0$, we can find the equilibrium values of the system (subscript "e" denotes the equilibrium values):

$$\begin{cases} x_{C,e} &= \dfrac{\gamma}{\delta}\left(\lambda - \eta\dfrac{s}{\delta}\right) \\ y_e &= \eta\dfrac{s}{\delta} \\ w_e &= \eta\rho x_{C,e} \end{cases} \tag{3.9}$$

We define χ, the Carrying Capacity for the population, to be equal to $x_{C,e}$ in (3.9), i.e., the equilibrium value of the population in the absence of Elites:

$$\chi = \frac{\gamma}{\delta}\left(\lambda - \eta\frac{s}{\delta}\right) \tag{3.10}$$

Carrying Capacity can be maximized if Nature's regeneration rate is maximal, i.e., if $y_e = \frac{\lambda}{2}$. This requires δ to be set equal to a value δ_* that can result in a steady state with the maximum (sustainable) Population, which in this paper we call the "optimal" value of δ. From the second equation in (3.9), it can be seen that δ_* is given by:

$$\delta_* = \frac{2\eta s}{\lambda} \tag{3.11}$$

The Maximum Carrying Capacity, χ_M, is thus given by:

$$\chi_M = \frac{\gamma}{\delta_*}\frac{\lambda}{2} = \frac{\gamma}{\eta s}\left(\frac{\lambda}{2}\right)^2 \tag{3.12}$$

3.4.2 Equilibrium when $x_E \geq 0$ and $\kappa = 1$ (No Inequality): Equitable Society

If we set $\kappa \equiv 1$ and $\beta_E \equiv \beta_C \equiv \beta$, we can reach an equilibrium state for which $x_E \geq 0$. This case models an equitable society of "Workers" and "Non-Workers". We need a dimensionless free parameter φ that sets the initial ratio of the Non-Workers to Workers:

$$\varphi = \frac{x_E(0)}{x_C(0)} \tag{3.13}$$

The equilibrium values of the system can then be expressed as follows:

$$\begin{cases} x_{C,e} &= \dfrac{\gamma}{\delta}\left(\lambda - \eta\dfrac{s}{\delta}(1+\varphi)\right) \\ x_{E,e} &= \varphi x_{C,e} \\ y_e &= \eta\dfrac{s}{\delta}(1+\varphi) \\ w_e &= \eta\rho(1+\varphi)x_{C,e} \end{cases} \tag{3.14}$$

The total population $x_e = x_{C,e} + x_{E,e}$ can still be maximized by choosing δ appropriately:

$$\delta_{**} = \frac{2\eta s}{\lambda}(1+\varphi) \tag{3.15}$$

This δ_{**} is larger than the optimal depletion factor given by (3.11). The difference arises because Workers have to produce more than they need just for themselves in order to support Non-Workers. For this choice of δ, total population is given by:

$$x_{e,M} = (1+\varphi)\frac{\gamma}{\delta_{**}}\frac{\lambda}{2} = \frac{\gamma}{\eta s}\left(\frac{\lambda}{2}\right)^2 \tag{3.16}$$

As can be seen from (3.16), maximum total population in equilibrium is independent of φ and conforms to the maximum carrying capacity given above by (3.12).

3.4.3 Equilibrium when $x_E \geq 0$ and $\kappa > 1$: Unequal Society

It is possible to attain equilibrium in an unequal society if we can satisfy the following condition:

$$\frac{\alpha_M - \beta_E}{\kappa(\alpha_M - \alpha_m)} = \frac{\alpha_M - \beta_C}{\alpha_M - \alpha_m} = \eta. \tag{3.17}$$

(The general condition $\alpha_m \leq \beta_E \leq \beta_C \leq \alpha_M$ must hold in all cases for an equilibrium to be feasible.)

The equilibrium values in this general case can be expressed as follows:

$$\begin{cases} x_{C,e} = \dfrac{\gamma}{\delta}\left(\lambda - \eta\dfrac{s}{\delta}(1+\kappa\psi)\right) \\ x_{E,e} = \psi x_{C,e} \\ y_e = \eta\dfrac{s}{\delta}(1+\kappa\psi) \\ w_e = \eta\rho(1+\kappa\psi)x_{C,e} \end{cases} \tag{3.18}$$

The free parameter, ψ, is the equilibrium ratio $x_{E,e}/x_{C,e}$, apparent from the second equation in (3.18). As opposed to φ, ψ cannot be easily related to the initial conditions; rather, it can be determined from the result of a simulation.

Again, the total population $x_e = x_{C,e} + x_{E,e}$ can be maximized by choosing δ appropriately:

$$\delta_{***} = \frac{2\eta s}{\lambda}(1+\kappa\psi) \tag{3.19}$$

This required depletion rate δ_{***} can be even larger than the optimal δ given by (3.15) depending upon the values of κ and ψ. In the presence of inequality, the maximum total population is no longer independent of κ and ψ and is smaller than the maximum carrying capacity given by equations (3.12) and (3.16):

$$x_{e,M} = (1+\psi)\frac{\gamma}{\delta_{***}}\frac{\lambda}{2} = \frac{\gamma}{\eta s}\left(\frac{\lambda}{2}\right)^2\left(\frac{1+\psi}{1+\kappa\psi}\right) \tag{3.20}$$

3.5 Scenarios

We discuss three sets of scenarios:

1. Egalitarian society (No-Elites): Scenarios in which $x_E = 0$.
2. Equitable society (with Workers and Non-Workers): Scenarios in which $x_E \geq 0$ but $\kappa \equiv 1$.
3. Unequal society (with Elites and Commoners): Scenarios in which $x_E \geq 0$ and $\kappa > 1$.

For all of these scenarios, we start the model with the typical parameter values and initial conditions given in table 3.1, unless otherwise stated. As indicated above, the values of κ and $x_E(0)$ determine the type of the society. Within each type of society, we obtain different scenarios by varying the depletion factor, δ.

In this section, we will show that HANDY is capable of modeling three distinct types of societies by changing κ and $x_E(0)$. A sustainable equilibrium can be found for each society by controlling δ. An appropriate choice of δ can make this equilibrium optimal, i.e., with maximum total population. Increasing δ above its optimal value makes the approach toward equilibrium oscillatory. Such an equilibrium is suboptimal, and the Carrying Capacity is below its maximum value, χ_M. It is also possible to reach a suboptimal equilibrium (a less than maximum, but sustainable population) by making δ *lower* than its optimal value. However, in the latter case, the approach toward equilibrium would be a soft landing rather than oscillatory.

Parameter Symbol	Parameter Name	Typical Value(s)
α_m	Normal (Minimum) Death rate	1.0×10^{-2}
α_M	Famine (Maximum) Death rate	7.0×10^{-2}
β_C	Commoner Birth rate	3.0×10^{-2}
β_E	Elite Birth rate	3.0×10^{-2}
s	Subsistence Salary per Capita	5.0×10^{-4}
ρ	Threshold Wealth per Capita	5.0×10^{-3}
γ	Regeneration rate of Nature	1.0×10^{-2}
λ	Nature Carrying Capacity	$1.0 \times 10^{+2}$
κ	Inequality factor	$1, 10, 100$
δ	Depletion (Production) Factor	None

(a) List of parameters in HANDY. κ and δ take different values for different scenarios.

Variable Symbol	Variable Name	Typical Initial Value(s)
x_C	Commoner Population	$1.0 \times 10^{+2}$
x_E	Elite Population	$0, 1, 25$
y	Nature	λ
w	Accumulated Wealth	0

(b) List of state variables in HANDY. $x_E(0)$ takes different values for different scenarios.

Table 3.1: Description of parameters and state variables used in HANDY. κ, δ, and x_E are varied to study various scenarios in three different types of societies. $x_E = 0$ defines an Egalitarian society with no Elites. $\kappa = 1$ defines an Equitable society with Workers and Non-Workers, represented by x_C and x_E in this case, respectively. $x_E \geq 0$ and $\kappa > 1$ define an unequal society with Elites and Commoners (x_E and x_C). As a reference, all other variables and functions in HANDY are also listed above. Subscript e denotes *equilibrium* value everywhere in this paper.

Variable Symbol	Variable Name	Defining Equation
w_{th}	Threshold Wealth	(3.6)
ω	Normalized Wealth	w/w_{th}
C_C	Commoner Consumption	(3.5) (figure 3.2)
C_E	Elite Consumption	(3.5) (figure 3.2)
α_C	Commoner Death Rate	(3.7) (figure 3.3)
α_E	Elite Death Rate	(3.7) (figure 3.3)
η	η	(3.8)
χ	Carrying Capacity (CC)	(3.10)
δ_*	Egalitarian Optimal δ	(3.11)
χ_M	Maximum Carrying Capacity (Max CC)	(3.12)
φ	Ratio of Non-Workers to Workers (Equitable)	(3.13)
δ_{**}	Equitable Optimal δ	(3.15)
ψ	Elite to Commoner Equilibrium Ratio (Unequal)	$x_{E,e}/x_{C,e}$
δ_{***}	Unequal Optimal δ	(3.19)

Table 3.2: As a reference, all other variables and functions in HANDY are listed in this table. Subscript e denotes *equilibrium* value everywhere in this paper.

When δ is increased even further, the society goes into cycles of prosperity and collapse. Increasing δ beyond a certain point will result in an irreversible Type-N (full) collapse, examples of which are presented in sections 3.5.1.4, 3.5.2.4, and 3.5.3.2. We give a full categorization of collapses in the next two paragraphs.

Running the model in different scenarios produces two kinds of collapses, either due to scarcity of labor (following an *inequality-induced* famine) or due to scarcity of Nature (depletion of natural resources). We categorize the former case as a Type-L (Disappearance of Labor) Collapse and the latter as a Type-N collapse (Exhaustion of Nature). In a Type-L collapse, growth of the Elite Population strains availability of resources for the Commoners. This causes decline of the Commoner Population (which does the labor), and consequently, decline of Wealth. Finally, Elite Population plummets since its source of subsistence, i.e., Wealth, has vanished. See figure 3.13 for an example of a Type-L collapse. This could represent a historical case such as the disappearance of the Mayan civilization in the Yucatan. Note that this type of collapse can only happen in an unequal society, because the major cause behind it is *inequality*.

A Type-N collapse, on the other hand, starts with an exhaustion of Nature, followed by a decline of Wealth that in turn, causes a fall of the Commoners and then the Elites. Depending on the depletion rate, Type-N collapses can be "reversible" or "irreversible". After a reversible collapse, regrowth of nature can trigger another cycle of prosperity, examples of which can be seen in figures 3.6 and 3.10. This could represent historical cases such as the Greek and Roman collapses.

When depletion is pushed beyond a certain limit, Nature fully collapses and the whole system completely collapses after that. This is why we call an irreversible Type-N collapse a "full" collapse. Examples of such collapses can be seen in figures 3.7, 3.11, and 3.14. This could represent a historical case such as the exhaustion of Nature on Easter Island. Type-N collapses can arise because of excessive depletion *only* (figures 3.7 and 3.11), or both excessive depletion and *inequality* (figure 3.14).

It is important to understand the inter-relation of the depletion factor, δ, and the Carrying Capacity, χ. The further δ is taken away from its optimal value, the further χ moves down from its maximum value, χ_M. An equilibrium can be reached if and only if χ is not too far away from χ_M, which means δ cannot be too far away from its optimal value, given by equations (3.11), (3.15), and (3.19) in the three types of societies under consideration. Note that in all of the scenario outputs presented below (for the three types of societies under consideration), Carrying Capacity (χ) and the Maximum Carrying Capacity (χ_M) are calculated from their defining equations (3.10) and (3.12), respectively.

Important note about the units of the vertical axis of all the subsequent graphs: Populations, x_C and x_E, and the Carrying Capacity, χ, are all normalized to the Maximum Carrying Capacity, χ_M. Nature and Wealth are both shown in units of Nature's capacity, λ. The top scale of the vertical axis of the graph pertains to Population(s) and Carrying Capacity; the middle scale pertains to Nature, which (normally) stays bounded by 1λ; and the bottom scale is for Wealth.

Note: All the simulations below use the Euler integration method with a time-step of 1 year and single precision.

3.5.1 Egalitarian Society (No-Elites): $x_E = 0$

In the four following scenarios, κ does not play any role since we set $x_E \equiv 0$. We start the depletion rate from $\delta = \delta_*$, the optimal equilibrium value that maximizes the Carrying Capacity, and increase it slowly to get additional scenarios. The horizontal red line in the graphs for the four scenarios of this section represents the *zero* population of Elites.

3.5.1.1 Egalitarian Society: Soft Landing to Equilibrium

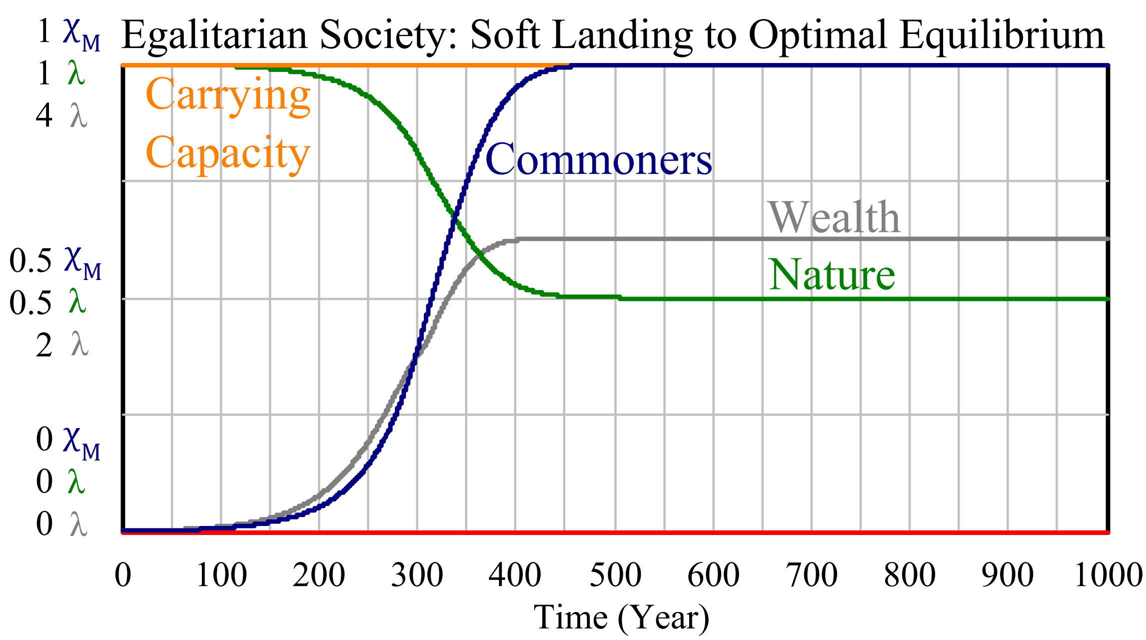

Figure 3.4: Soft landing to the optimal equilibrium when Elite population (marked in red) equals zero. Final population reaches the carrying capacity, which is at its maximum value, χ_M, in this scenario.

For the scenario in figure 3.4, $\delta = \delta_* = 6.67 \times 10^{-6}$. Therefore, the carrying capacity, χ, is at its maximum level, χ_M. Notice that Nature also settles to $y_e = \lambda/2$, which is the value that results in the maximum regeneration rate. This maximal regeneration can in turn support a maximum sustainable depletion and population.

If we set $\delta < \delta_*$, we still see a soft landing to the carrying capacity, χ. However, χ would be at a lower level than χ_M because a lower-than-optimal δ does not correspond to the maximum regeneration of nature, which is a necessity if we want to have the *maximum sustainable* population. The advantage of a lower-than-optimal δ is a higher equilibrium level (compared to $\lambda/2$) for Nature.

Choosing a depletion rate, δ, that is too small to produce enough to feed the population would result in a collapse, and thus make any equilibrium impossible even though Nature stays at its maximum capacity. Of course, this would not occur in the real world as the urge for survival guarantees humans extract their basic needs from nature.

3.5.1.2 Egalitarian Society: Oscillatory Approach to Equilibrium

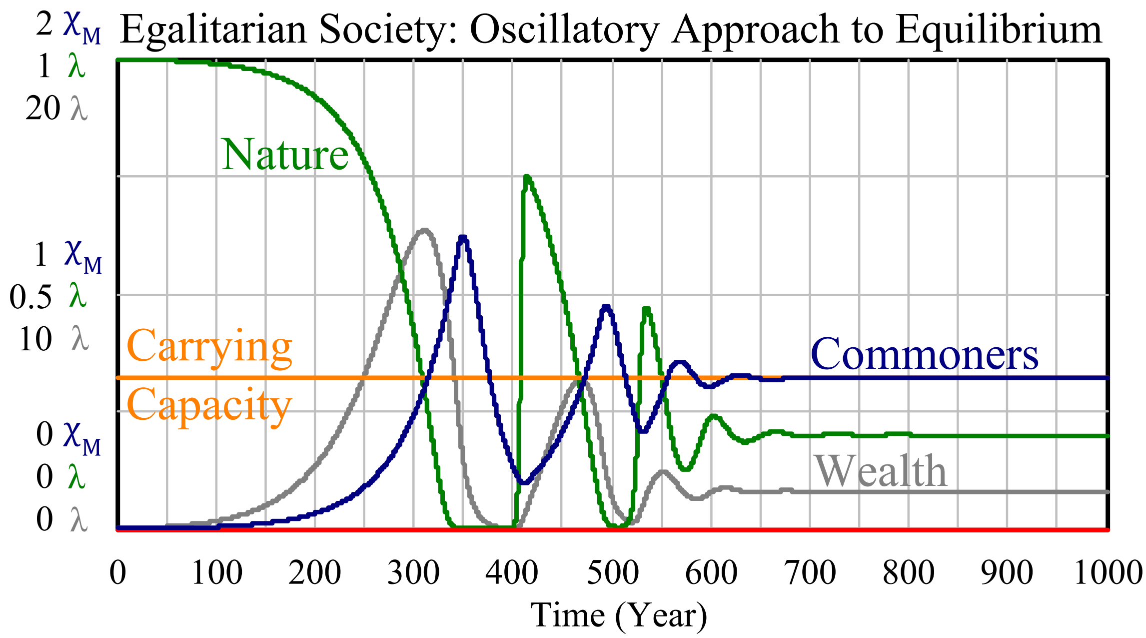

Figure 3.5: Oscillatory approach to equilibrium when Elite population (marked in red) equals zero. Final population converges to the carrying capacity, which is lower than its maximum value, χ_M, in this scenario.

For the scenario in figure 3.5, δ is increased to $\delta = 2.5\delta_* = 1.67 \times 10^{-5}$. As can be seen from figure 3.5, the carrying capacity, χ, is lower than its maximum value, χ_M. Population initially overshoots the carrying capacity, then oscillates, and eventually converges to it since the amount of overshoot is not too large, just about the order of χ. Note that at the time the (total) population overshoots the Carrying Capacity, the Wealth also reaches a maximum and starts to decline.

3.5.1.3 Egalitarian Society: Cycles of Prosperity, Overshoot, Collapse, and Revival

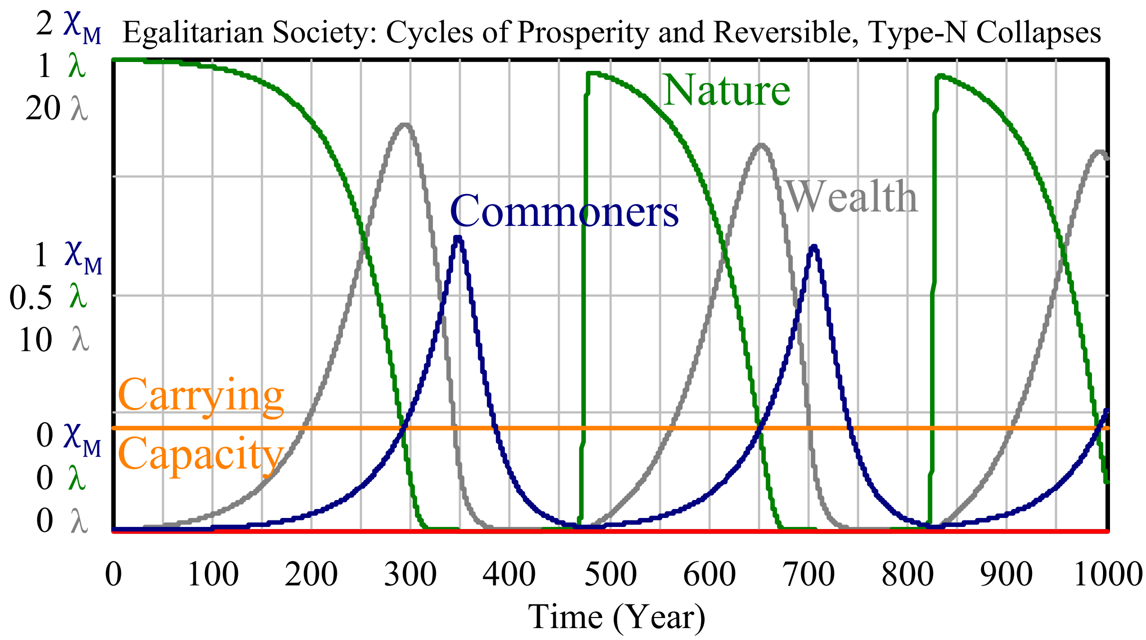

Figure 3.6: Cycles of prosperity, overshoot, (reversible Type-N) collapse, and revival when Elite population (marked in red) equals zero.

For the scenario in figure 3.6, δ is increased to $\delta = 4\delta_* = 2.67 \times 10^{-5}$. As can be seen, Population, Nature and Wealth all collapse to a very small value. However, after depletion becomes small due to very low number of workers, Nature gets a chance to grow back close to its capacity, λ. The regrowth of Nature kicks off another cycle of prosperity which ends with another collapse. Simulation results show that these cycles, ending in Type-N collapses (i.e., those that start due to scarcity of Nature), repeat themselves indefinitely. Therefore, such cycles represent "reversible" Type-N collapses. This reversibility is possible as long as δ stays within a "safe" neighborhood of δ_*.

3.5.1.4 Egalitarian Society: Irreversible Type-N Collapse (Full Collapse)

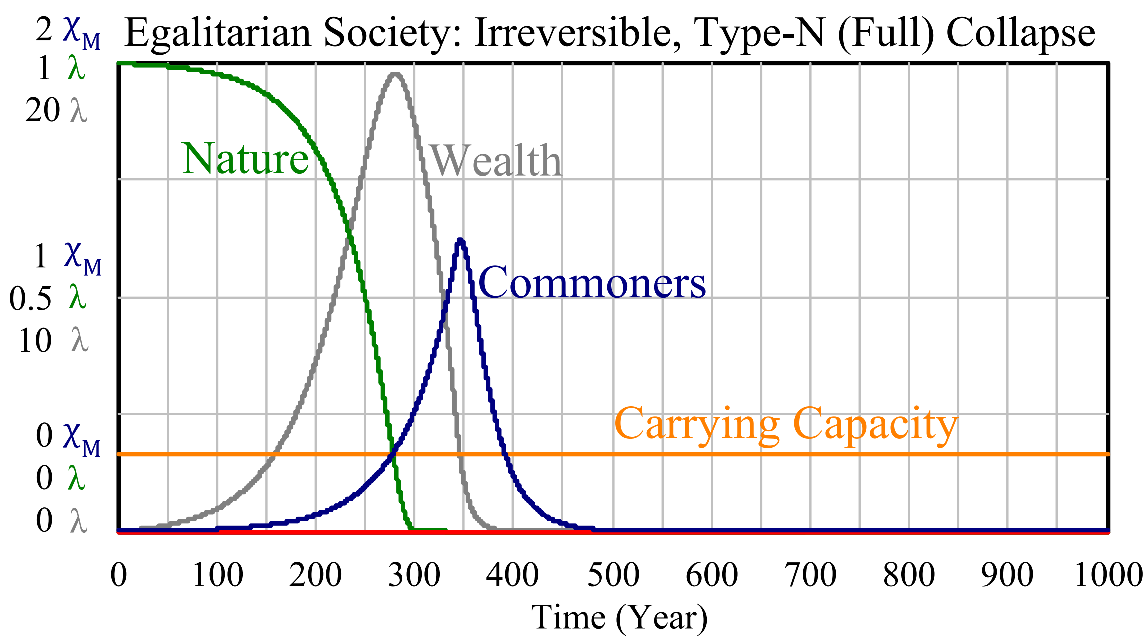

Figure 3.7: Irreversible Type-N collapse (full collapse) when Elite population (marked in red) equals zero. All the state variables collapse to *zero* in this scenario due to over-depletion.

For the scenario in figure 3.7, δ is increased further to $\delta = 5.5\delta_* = 3.67E-5$. The overshoot is so large that it forces Population, Nature and Wealth into a full collapse, after which there is no recovery. This is a generic type of collapse that can happen for any type of society due to over-depletion. See sections 3.5.2.4 and 3.5.3.2 for examples of irreversible Type-N collapses in equitable and unequal societies, respectively. We include further discussion of these two types of collapses in section 3.6.

We observe that the accumulated Wealth delays a decline of the population even after Nature has declined well below its capacity, λ. Therefore, population keeps growing and depleting Nature until Nature is fully exhausted. At that instance, i.e., when $y = 0$, Wealth cannot grow any further; indeed, it starts plummeting, causing a sharp fall of the population level, and eventually its full, irreversible collapse.

3.5.2 Equitable Society (with Workers and Non-Workers): $\kappa = 1$

We take the parameter values and the initial conditions to be the same as in table 3.1, except that this time we set $x_E(0) = 25$ ($\varphi = 0.25$) and $\kappa = 1$. We start with the optimal depletion per capita $\delta = \delta_{**}$, which will sustain the maximum population (see (3.15)), and will gradually increase it in order to get the additional scenarios in this subsection. Notice that in these cases, x_C describes the Working Population, while x_E describes the Non-Working Population. Everybody consumes at the same level, since we set $\kappa = 1$, i.e., we assume there is no inequality in consumption level for Workers and Non-Workers.

3.5.2.1 Equitable Society: Soft Landing to Optimal Equilibrium

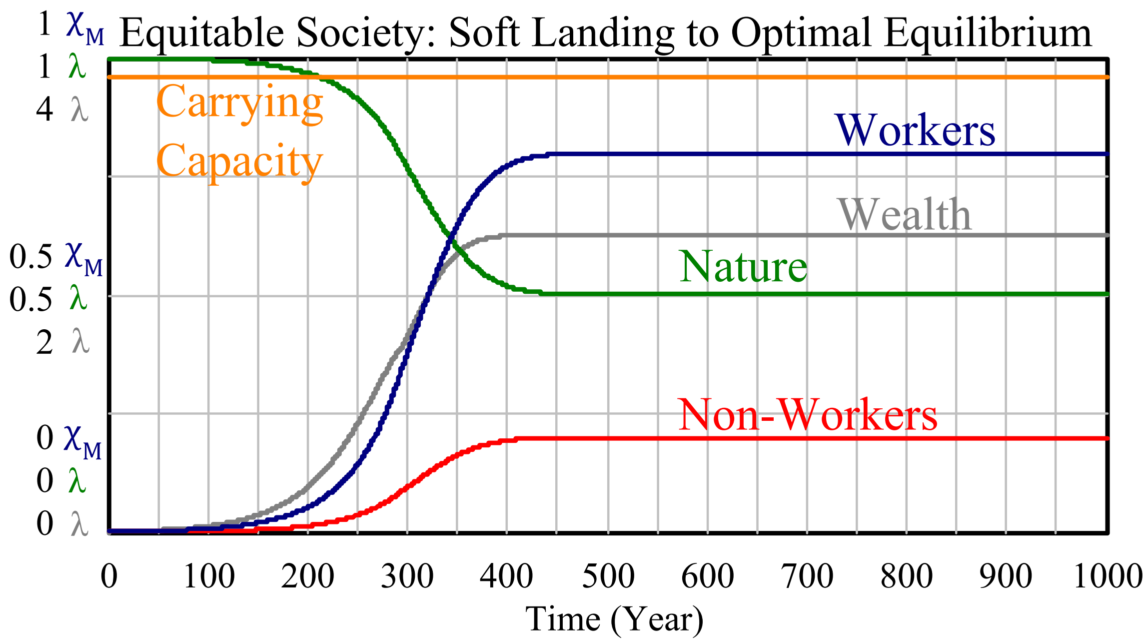

Figure 3.8: Equilibrium in the presence of both Workers and Non-Workers can be attained with slow growth and equitable salaries.

For the scenario in figure 3.8, $\delta = \delta_{**} = 8.33 \times 10^{-6}$. Notice that this is larger than the optimal value in the absence of Non-Workers $\delta_* = 6.67 \times 10^{-6}$ even though all the other parameters are identical to those in section 3.5.1.1. This difference arises because $x_E \neq 0$, which in turn forces the Workers to produce extra in order to support the Non-Workers. Now, $\chi < \chi_M$ because $\delta = \delta_{**} \neq \delta_*$. However, by setting $\delta = \delta_{**}$, the optimal value of δ in the presence of Non-Workers, the total population, $x_C + x_E$ still reaches the maximum Carrying Capacity, χ_M, the same as in section 3.5.1. See equation (3.16) and section 3.4.2 for a mathematical description.

Similar comments as in section 3.5.1.1 apply here when we choose a lower-than-optimal δ.

3.5.2.2 Equitable Society: Oscillatory Approach to Equilibrium

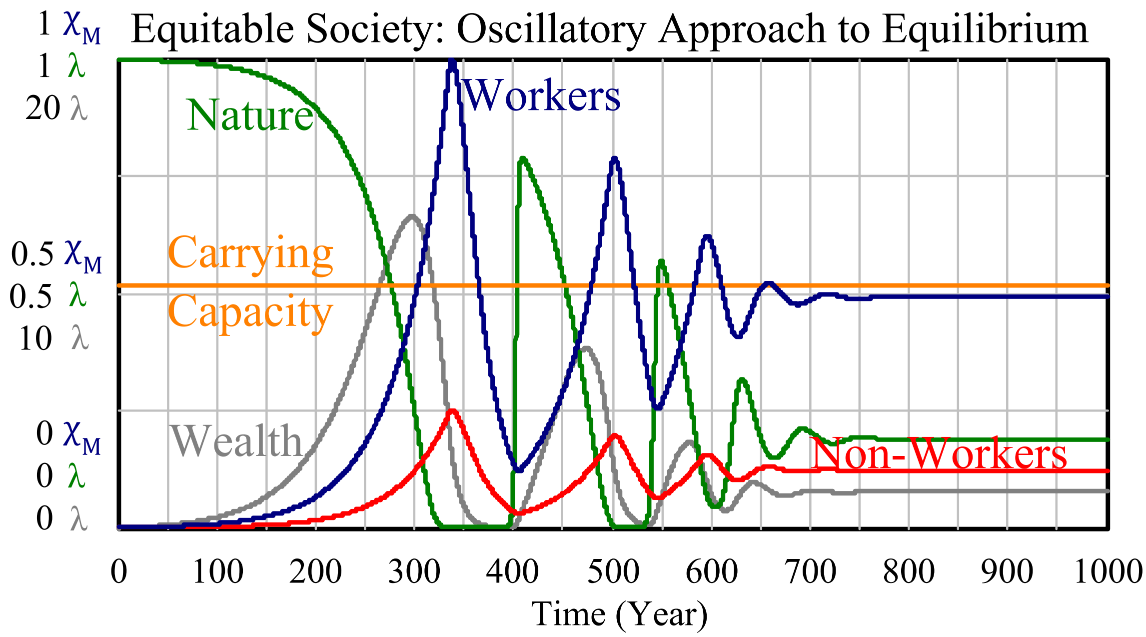

Figure 3.9: Oscillatory approach to equilibrium in the presence of both Workers and Non-Workers is possible when the overshoot is not too large.

For the scenario in figure 3.9, $\delta = 2.64\delta_{**} = 2.20 \times 10^{-5}$. The total population is equal to the actual Carrying Capacity (smaller than the maximum Carrying Capacity).

3.5.2.3 Equitable Society: Cycles of Prosperity, Overshoot, Collapse, and Revival

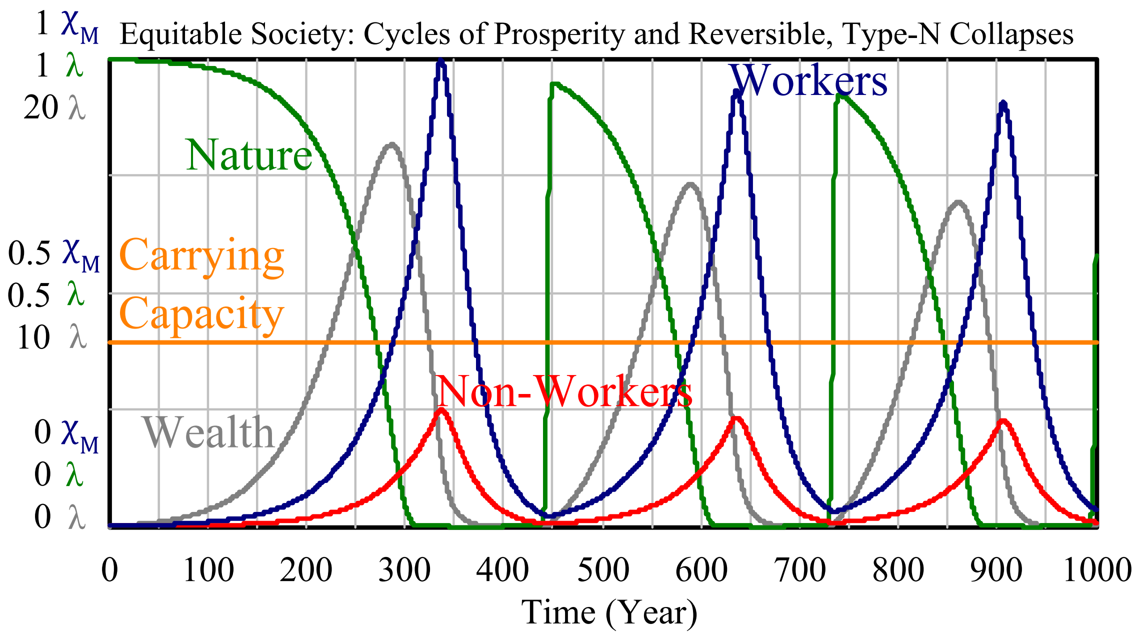

Figure 3.10: Cycles of prosperity, overshoot, (reversible Type-N) collapse, and revival in the presence of Workers and Non-Workers.

For the scenario in figure 3.10, $\delta = 3.46\delta_{**} = 3.00 \times 10^{-5}$. The result is analogous to figure 3.6 which corresponds to section 3.5.1.3. As before, the time at which the total population overshoots the actual Carrying Capacity is indicated by the fact that Wealth starts to decrease. After each cycle of prosperity, there is a partial, reversible Type-N collapse.

3.5.2.4 Equitable Society: Full Collapse

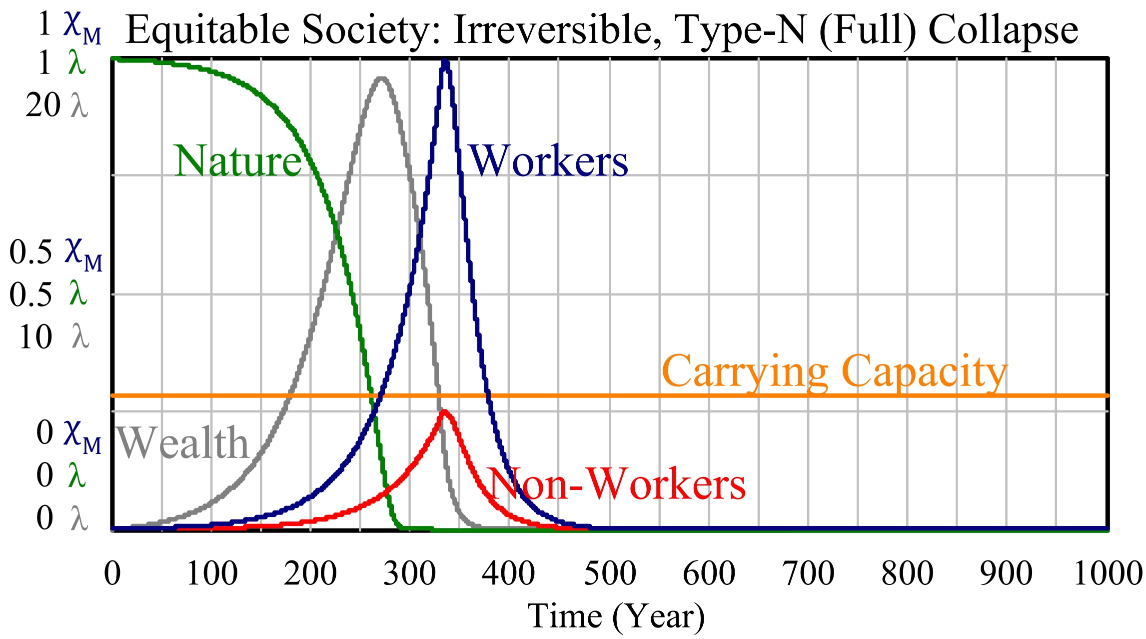

Figure 3.11: Irreversible Type-N collapse (full collapse) happens after a period of very fast growth.

For the scenario in figure 3.11, $\delta = 5\delta_{**} = 4.33 \times 10^{-5}$. Once again, we can see how an irreversible Type-N (full) collapse of Population, Nature, and Wealth can occur due to over-depletion of natural resources as a result of high depletion per capita.

3.5.2.5 Equitable Society: Preventing a Full Collapse by Decreasing *Average* Depletion per Capita

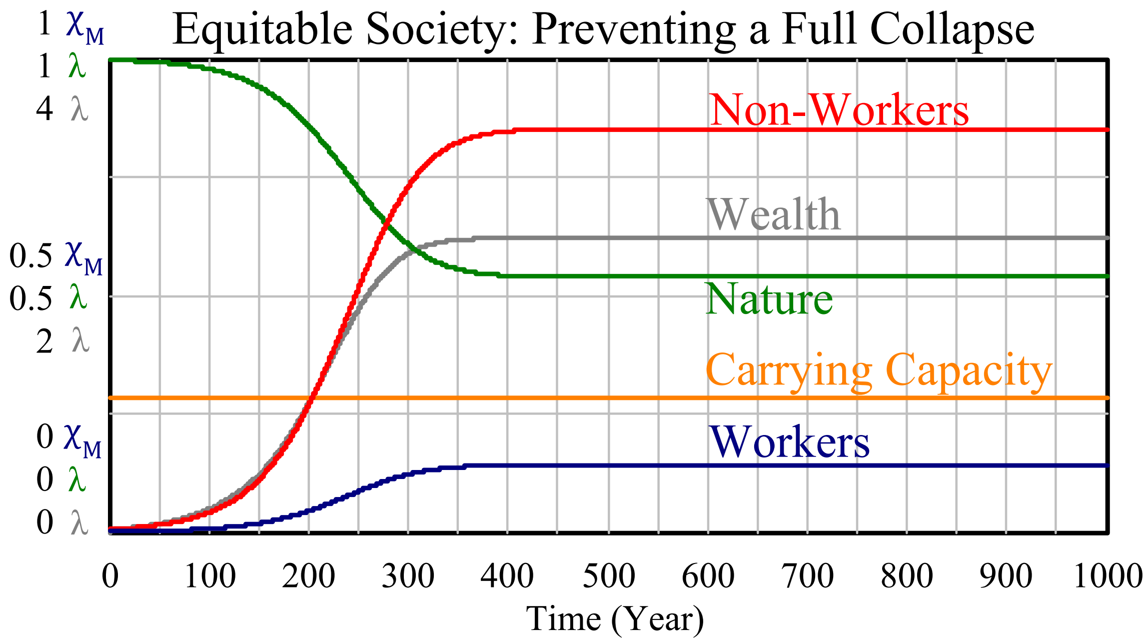

Figure 3.12: The full collapse that happened in the previous scenario, figure 3.11 of section 3.5.2.4, can be prevented by reducing the *average* depletion per capita. This can be achieved by either increasing the ratio of the Non-Working to Working population (high δ, high φ) or decreasing the average workload per worker, i.e., decreasing total work hours per week (low δ, low φ).

The case in figure 3.12 is similar to the previous case (see section 3.5.2.4 and figure 3.11), except that we raised the ratio of Non-Workers to Workers, φ, from 0.25 to 6. This corresponds to changing $x_E(0)$ from 25 to 600, while keeping $x_C(0) = 100$. By increasing the ratio of non-workers to workers, a sustainable equilibrium can be reached due to lower *average* depletion per capita —an equivalent δ if everyone contributed equally to labor. This could also be interpreted as modeling a reduction in the average workload per worker.

3.5.3 Unequal Society (with Elites and Commoners): $x_E \geq 0$ and $\kappa > 1$

In our examples of an unequal society, the Elites (per capita) consume $\kappa \sim 10$ to 100 times more than the Commoners. Their population, plotted in red, is multiplied by κ to represent their equivalent impact because of their higher consumption. That is why we use the label "*Equivalent* Elites" on the graphs in this section, 3.5.3.

In the first two cases, we discuss two distinct, but generic types of collapse in an unequal society. In these two scenarios, $\kappa = 100$. Then we will show possibility of reaching an equilibrium by reducing κ to 10 and adjusting the birth rates β_E and β_C independently. These two $\kappa = 10$ scenarios show that in order to reach a sustainable equilibrium in an unequal society, it is necessary to have policies that limit inequality and ensure birth rates remain below critical levels.

3.5.3.1 Unequal Society: Type-L Collapse (Labor Disappears, Nature Recovers)

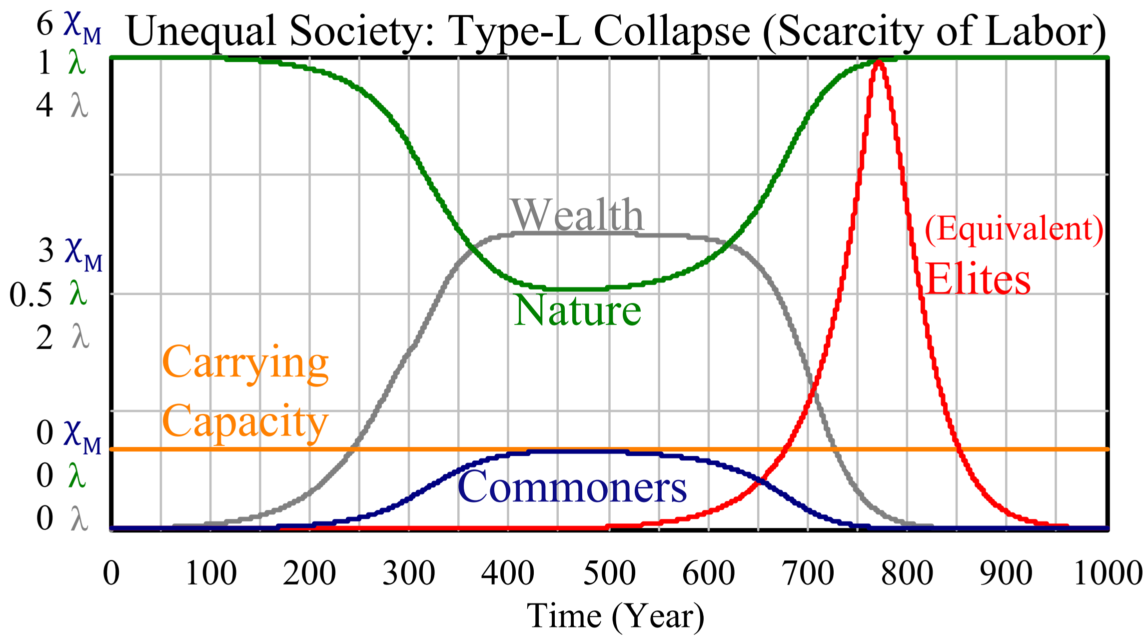

Figure 3.13: Population collapse following an apparent equilibrium due to a small initial Elite population when $\kappa = 100$. This scenario also shows a different route to a collapse, in which, although Nature eventually recovers, population does not.

This scenario, presented in figure 3.13, is precisely the same as the equilibrium without Elites case presented in section 3.5.1.1 (figure 3.4) except that here we set $x_E(0) = 1.0 \times 10^{-3}$. This is indeed a very small initial seed of Elites. The two scenarios look pretty much the same up until about $t = 500$ years after the starting time of the simulation. The Elite population starts growing significantly only after $t = 500$, hence depleting the Wealth and causing the system to collapse. Under this scenario, the system collapses due to worker scarcity even though natural resources are still abundant, but because the depletion rate is optimal, it takes more than

400 years after the Wealth reaches a maximum for the society to collapse. In this example, Commoners die out first and Elites disappear later. This scenario shows that in a society that is otherwise sustainable, the highly unequal consumption of elites will still cause a collapse.

This scenario is an example of a Type-L collapse in which both Population and Wealth collapse but Nature recovers (to its maximum capacity, λ, in the absence of depletion). Scarcity of workers is the initial cause of a Type-L collapse, as opposed to scarcity of Nature for a Type-N collapse.

3.5.3.2 Unequal Society: Irreversible Type-N Collapse (Full Collapse)

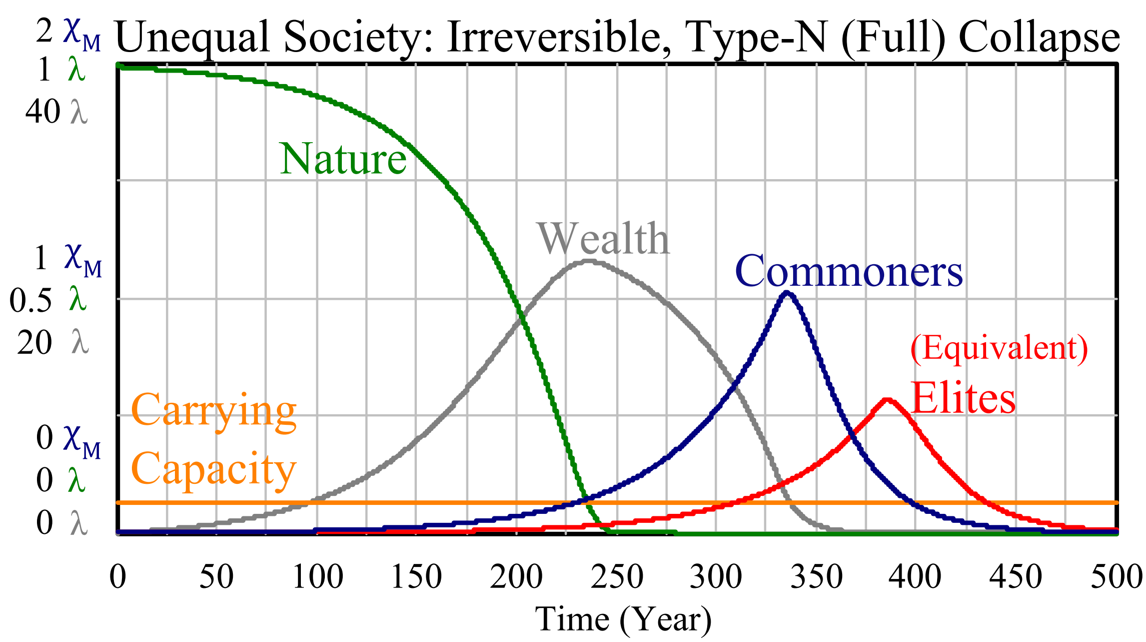

Figure 3.14: A fast full collapse due to both over-depletion and inequality ($\kappa = 100$).

The typical scenario in figure 3.14 for a full collapse is the result of running the model with the parameter values and initial conditions given by table 3.1. Examples of irreversible Type-N (full) collapses in the egalitarian and equitable societies are presented in sections 3.5.1.4 (figure 3.7) and 3.5.2.4 (figure 3.11).

We set a small initial seed of $x_E(0) = 0.20$, $\kappa = 100$, and a large depletion $\delta = 1.0 \times 10^{-4}$, so that both the depletion $\delta = 15\delta_*$ and the inequality coefficient $\kappa = 100$ are very large. This combination results in a full collapse of the system with no recovery. The Wealth starts declining as soon as the Commoner's population goes beyond its carrying capacity, and then the full collapse takes only about 250 additional years. The declining Wealth causes the fall of the Commoner's population (workers) with a time lag. The fast reduction in the number of workers combined with scarcity of natural resources causes the Wealth to decline even faster than before. As a result, the Elites —who could initially survive the famine due to their unequal access to consumable goods ($\kappa = 100$)— eventually also die of hunger. Note that because both depletion and inequality are large, the collapse takes place faster and at a much lower level of population than in the previous case (see section 3.5.3.1, figure 3.5.3.1) with a depletion rate of $\delta = \delta_*$.

3.5.3.3 Unequal Society: Soft Landing to Optimal Equilibrium

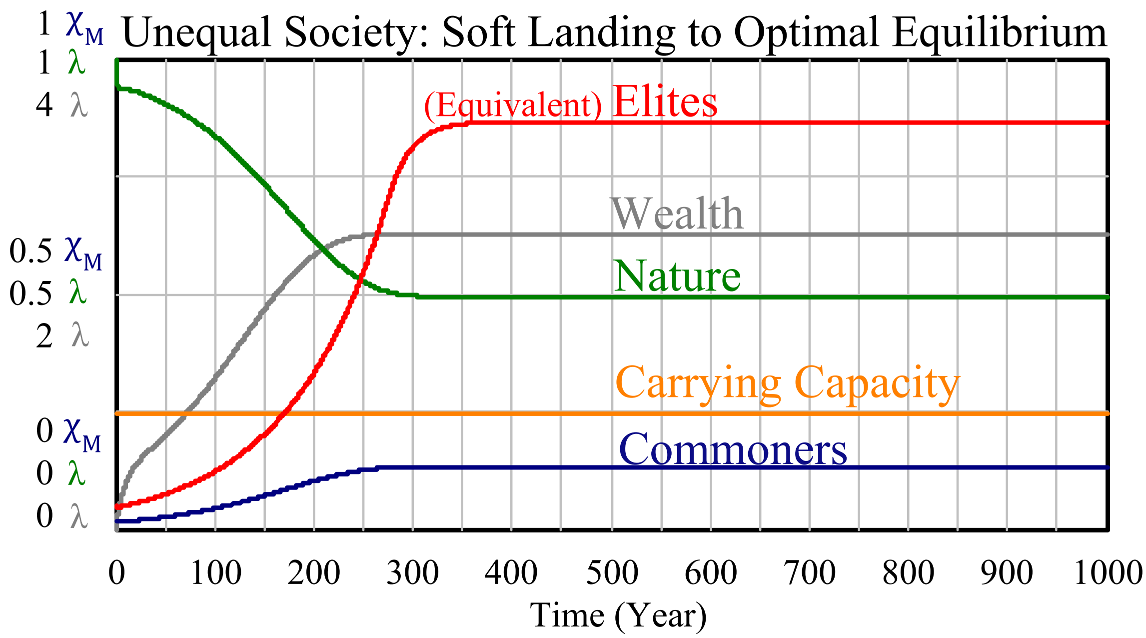

Figure 3.15: With moderate inequality ($\kappa = 10$), it is possible to attain an optimal equilibrium by controlling the birth rates.

The following parameter values and initial values can produce the current scenario (the rest are exactly the same as in table 3.1):

$$\begin{cases} \beta_C = 6.5 \times 10^{-2} & \beta_E = 2.0 \times 10^{-2} \\ x_C(0) = 1.0 \times 10^{+4} & x_E(0) = 3.0 \times 10^{+3} \\ \kappa = 10 & \delta = 6.35 \times 10^{-6} \end{cases} \tag{3.21}$$

The value for δ used in this scenario is δ_{***} given by equation (3.19). It must be remembered that $\psi = 0.65$ is not a parameter that we can choose. However, it can be read from the result of the simulation since it is the equilibrium ratio of the

Elite to Commoner population. See the second equation in (3.18). On the other hand, $\eta = \frac{1}{12}$ is determined by the death and birth rates as well as the inequality coefficient. These parameters are chosen in order to satisfy (3.17), the necessary condition for attaining an equilibrium in an unequal society.

The same comments as in section 3.5.1.1 hold here if we choose a lower-than-optimal δ.

3.5.3.4 Unequal Society: Oscillatory Approach to Equilibrium

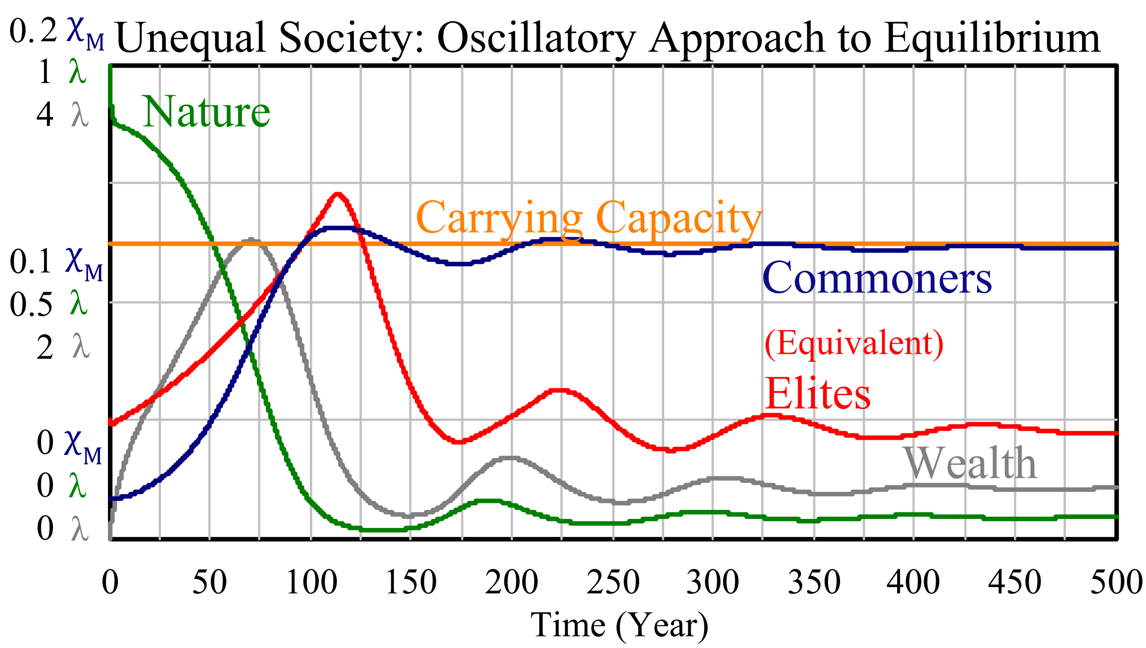

Figure 3.16: With $\delta \gtrsim \delta_{***}$, it is still possible to oscillate and converge to an equilibrium ($\kappa = 10$).

The parameter values and initial conditions in the scenario presented in figure 3.16 are exactly the same as the previous scenario, presented in figure 3.15, except for δ. It is increased to 1.3×10^{-5}, almost $2\delta_{***}$. This results in a much lower Carrying Capacity compared to 3.5.3.3, as can be seen from a comparison of figures

3.15 and 3.16. Therefore, the total final population in the present scenario is much less than the total final population in the previous scenario, 3.5.3.3 (figure 3.15).

3.6 Discussion of Results

We conducted a series of experiments with the HANDY model, considering first an egalitarian society without Elites ($x_E = 0$), next an equitable society ($\kappa = 1$) where Non-Workers and Workers are equally paid, and finally an unequal society whose Elites consume κ times more than the Commoners. The model was also used to find a sustainable equilibrium value and the maximum carrying capacity within each of these three types of societies.

3.6.1 Unequal Society

The scenarios most closely reflecting the reality of our world today are found in the third group of experiments (see the scenarios for an unequal society in section 3.5.3), where we introduced economic stratification. Under such conditions, we find that collapse is difficult to avoid, which helps to explain why economic stratification is one of the elements consistently found in past collapsed societies. Importantly, in the first of these unequal society scenarios, 3.5.3.1, *the solution appears to be on a sustainable path for quite a long time*, but even using an optimal depletion rate (δ_*) and starting with a very small number of Elites, the Elites eventually consume too much, resulting in a famine among Commoners that eventually causes the collapse of society. It is important to note that this Type-L collapse is *due to* *an inequality-induced famine that causes a loss of workers, rather than a collapse of Nature*. Despite appearing initially to be the same as the sustainable optimal solution obtained in the absence of Elites, economic stratification changes the final result: Elites' consumption keeps growing until the society collapses. The Mayan collapse —in which population never recovered even though nature *did* recover— is an example of a Type-L collapse, whereas the collapses in the Easter Island and the Fertile Crescent —where nature was depleted— are examples of a Type-N collapse.

In scenario 3.5.3.2, with a larger depletion rate, the decline of the Commoners occurs faster, while the Elites are still thriving, but eventually the Commoners collapse completely, followed by the Elites. It is important to note that in both of these scenarios, the Elites —due to their wealth— do not suffer the detrimental effects of the environmental collapse until much later than the Commoners. This buffer of wealth allows Elites to continue "business as usual" despite the impending catastrophe. It is likely that this is an important mechanism that would help explain how historical collapses were allowed to occur by elites who appear to be oblivious to the catastrophic trajectory (most clearly apparent in the Roman and Mayan cases). This buffer effect is further reinforced by the long, apparently sustainable trajectory prior to the beginning of the collapse. While some members of society might raise the alarm that the system is moving towards an impending collapse and therefore advocate structural changes to society in order to avoid it, Elites and their supporters, who opposed making these changes, could point to the long sustainable trajectory "so far" in support of doing nothing.

The final two scenarios in this set of experiments, 3.5.3.3 and 3.5.3.4, are designed to indicate the kinds of policies needed to avoid this catastrophic outcome. They show that, in the context of economic stratification, inequality must be greatly reduced and population growth must be maintained below critical levels in order to avoid a societal collapse [Daly, 2008].

3.6.2 Egalitarian Society

In order to further understand what conditions are needed to avoid collapse, our first set of experiments model a society without economic stratification and start with parameter values that make it possible to reach a maximum carrying capacity (scenario 3.5.1.1). The results show that in the absence of Elites, if the depletion per capita is kept at the optimal level of δ_*, the population grows smoothly and asymptotes the level of the maximum carrying capacity. This produces a soft-landing to equilibrium at the maximum sustainable population and production levels.

Increasing the depletion factor slightly (scenario 3.5.1.2) causes the system to oscillate, but still reach a sustainable equilibrium, although, importantly, at a lower carrying capacity. Population overshoots its carrying capacity, but since the overshoot is not by too much —of the order of the carrying capacity— the population experiences smaller collapses that can cause it to oscillate and eventually converge to a sustainable equilibrium. Thus, while social disruption and deaths would occur, a total collapse is avoided.

A further increase in the depletion factor (scenario 3.5.1.3) makes the system experience oscillatory periods of growth, very large overshoots and devastating collapses that almost wipe out society, but the eventual recovery of Nature allows for the cycle to be repeated.

Increasing the depletion factor even further (scenario 3.5.1.4) results in a complete collapse of the system. This shows that depletion alone, if large enough, can result in a collapse — even in the absence of economic stratification.

3.6.3 Equitable Society (with Workers and Non-Workers)

As the second set of experiments (presented in section 3.5.2) show, HANDY allows us to model a diverse range of societal arrangements. In this set of experiments, choosing $x_E \geq 0$ and $\kappa = 1$ has allowed us to model a situation that can be described as having Workers and Non-Workers with the same level of consumption, i.e., with no economic stratification. The Non-Workers in these scenarios could represent a range of societal roles from students, retirees, and disabled people, to intellectuals, managers, and other non-productive sectors. In this case, the Workers have to deplete enough of Nature to support both the Non-Workers and themselves.

The first scenario, 3.5.2.1, shows that even with a population of Non-Workers, the total population can still reach a sustainable equilibrium without a collapse. In scenario 3.5.2.2, we find that increasing the depletion factor induces a series of overshoots and small collapses where population eventually converges to a lower sustainable equilibrium. Like in an egalitarian society, scenario 3.5.2.3 shows us that increasing the depletion parameter further results in cycles of large overshooting, major collapses, and then eventual recovery of Nature. Scenario 3.5.2.4 shows us that increasing depletion per capita further can produce an irreversible Type-N collapse.

Finally, scenario 3.5.2.5, which is a replication of 3.5.2.4 with a much higher ratio of Non-Workers to Workers, shows that a collapse in an equitable society could be avoided by reducing the average depletion per capita. We note that this scenario could also represent a situation where, rather than having paid Non-Workers, the workload per capita is reduced, with the whole population working "fewer days a week". Such a "work-sharing" policy has been successfully implemented in Germany over the past few years for reducing unemployment [Baker and Hasset, 2012; Hasset, 2009]. Moreover, Knight et al. [2013] show, through a panel analysis of data for 29 high-income OECD countries from 1970 to 2010, that reducing work hours can contribute to sustainability by reducing ecological strain. This conclusion agrees with our comparison of the two scenarios, 3.5.2.5 and 3.5.2.4, presented above.

3.6.4 HANDY and Brander-Taylor Model

As previously mentioned, a similar use of the predator-prey approach was applied in the pioneering work of Brander and Taylor [1998] (BT) to study the historical rise and fall of the Easter Island population. In comparison to their model, with just two equations for Population and Nature, the introduction of Elites and Commoners, and accumulated Wealth, results in a greater variety and broader spectrum of potential solutions. Moreover, the collapse scenario presented in BT is somewhat different from the ones presented above. As a matter of fact, the collapse scenario presented in figure 3 of BT seems to be more of an oscillatory approach to equilibrium, similar to the one shown in our figure 3.5, and not a collapse in the sense that we define in this paper. Furthermore, the carrying capacity, in the sense we define in this paper, is also different from what Brander and Taylor [1998] call carrying capacity. Indeed, their carrying capacity (K) is our Nature's capacity, λ, which is the maximum size Nature can reach, whereas Carrying Capacity in HANDY is the population level that can be supported by a given level of natural resources. Furthermore, BT's carrying capacity is a constant, whereas Carrying Capacity in HANDY adjusts according to the level of depletion of Nature.

While sharing certain similarities with the Brander and Taylor model, our more complex model structure and the use of different assumptions, allows our model to apply to multiple types of societies with varying socioeconomic structures. Thus, unlike works that tend to study further implications of the two-dimensional model of BT [Anderies, 2000], the model we have developed introduces a more complex set of possible feedbacks and nonlinear dynamics, and a greater spectrum of potential outcomes. This allows HANDY to model a different and wider set of thought experiments.

An important feature of HANDY that distinguishes it from Predator-Prey, BT, and other similar models [Anderies, 1998; Dalton et al., 2005; Erickson and Gowdy, 2000; Reuveny and Decker, 2000] is its native capability for producing irreversible collapses due to the structure for accumulation of wealth. Our approach also differs from models like D'Alessandro [2007] that can produce irreversible collapses but only through explicit introduction of a critical depensation mechanism into the model.

The dynamics produced by HANDY offer the possibility of irreversible collapses without having to introduce such an additional mechanism into the model. See section 3.5.1.4 for an explanation of irreversible collapses in HANDY. [1]

3.7 Summary

Collapses of even advanced civilizations have occurred many times in the past five thousand years, and they were frequently followed by centuries of population and cultural decline and economic regression. Although many different causes have been offered to explain individual collapses, it is still necessary to develop a more general explanation. In this paper we attempt to build a simple mathematical model to explore the essential dynamics of interaction between population and natural resources. It allows for the two features that seem to appear across societies that have collapsed: the stretching of resources due to strain placed on the ecological carrying capacity, and the division of society into Elites (rich) and Commoners (poor).

The Human And Nature DYnamical model (HANDY) was inspired by the Predator and Prey model, with the human population acting as the predator and nature being the prey. When small, Nature grows exponentially with a regeneration coefficient γ, but it saturates at a maximum value λ. As a result, the maximum regeneration of nature takes place at $\lambda/2$, not at the saturation level λ. The Commoners produce wealth at a per capita depletion rate δ, and the depletion is also

[1] We wish to acknowledge and thank reviewer No. 1 for highlighting these very important points to us.

proportional to the amount of nature available. This production is saved as accumulated wealth, which is used by the Elites to pay the Commoners a subsistence salary, s, and pay themselves κs, where κ is the inequality coefficient. The populations of Elites and Commoners grow with a birth rate β and die with a death rate α which remains at a healthy low level when there is enough accumulated food (wealth). However, when the population increases and the wealth declines, the death rate increases up to a famine level, leading to population decline.

We show how the carrying capacity —the population that can be indefinitely supported by a given environment [Catton, 1980a]— can be defined within HANDY, as the population whose total consumption is at a level that equals what nature can regenerate. Since the regrowth of Nature is maximum when $y = \lambda/2$, we can find the optimal level of depletion (production) per capita, δ_* in an egalitarian society where $x_E \equiv 0$, $\delta_{**}(\geq \delta_*)$ in an equitable society where $\kappa \equiv 1$, and δ_{***} in an unequal society where $x_E \geq 0$ and $\kappa > 1$.

In sum, the results of our experiments, discussed in section 3.6, indicate that either one of the two features apparent in historical societal collapses —over-exploitation of natural resources and strong economic stratification— can independently result in a complete collapse. Given economic stratification, collapse is very difficult to avoid and requires major policy changes, including major reductions in inequality and population growth rates. Even in the absence of economic stratification, collapse can still occur if depletion per capita is too high. However, collapse can be avoided and population can reach equilibrium if the per capita rate of depletion of nature is reduced to a sustainable level, and if resources are distributed in a reasonably equitable fashion.

In the upcoming generations of HANDY, we plan to develop several extensions including: (1) disaggregation of Nature into nonrenewable stocks, regenerating stocks, and renewable flows, as well as the introduction of an investment mechanism in accessibility of natural resources, in order to study the effects of investment in technology on resource choice and production efficiency; (2) making inequality (κ) endogenous to the model structure; (3) introduction of "policies" that can modify parameters such as depletion, the coefficient of inequality, and the birth rate; and, (4) introduction of multiple coupled regions to represent countries with different policies, trade of carrying capacity, and resource wars.

Those interested in obtaining the model code can contact the authors.

3.8 Acknowledgements

We are grateful to Profs. Matthias Ruth, Victor Yakovenko, Herman Daly, Takemasa Miyoshi, Jim Carton, Fernando Miralles-Wilhelm, Ning Zeng, and Drs. Robert Cahalan and Steve Penny for many useful discussions. Study of the "Equitable Society" scenarios (i.e., with Workers and Non-Workers), the scenario presented in section 3.5.2.5, in particular, was suggested by V. Yakovenko. We would also like to thank anonymous reviewer No. 1 for having highlighted to us the importance of the capability of HANDY to naturally produce irreversible collapses, which is not found in earlier models. We would especially like to thank the editors of this journal for alerting us to the model and work done by Brander and Taylor, of which we were unaware, and allowing us to revise our article to account for this new information.

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Based on the media reports on a pre-publication version of this paper, NASA issued the official statement contained in Release 14-082.

http://www.nasa.gov/press/2014/march/nasa-statement-on-sustainability-study/

March 20th , 2014

RELEASE 14-082 NASA Statement on Sustainability Study

The following is a statement from NASA regarding erroneous media reports crediting the agency with an academic paper on population and societal impacts.

“A soon-to-be published research paper 'Human and Nature Dynamics (HANDY): Modeling Inequality and Use of Resources in the Collapse or Sustainability of Societies' by University of Maryland researchers Safa Motesharrei and Eugenia Kalnay, and University of Minnesotas Jorge Rivas was not solicited, directed or reviewed by NASA. It is an independent study by the university researchers utilizing research tools developed for a separate NASA activity.

“As is the case with all independent research, the views and conclusions in the paper are those of the authors alone. NASA does not endorse the paper or its conclusions.”

Chapter 4: Exploring Water Management Options with COWA: A Coupled Human-Water-Climate Model

Water is, and has always been, a critical resource for survival of civilizations and a key to prosperity of societies. Over the past several decades, demand for freshwater has increased significantly due to growth of both population and consumption. Such soaring demands have put serious strain on freshwater sources at many regions of the world, and climate change can only worsen the uncertainty in availability of needed freshwater. Therefore, it is essential to study the water system in conjunction with the Earth system and the Human system. Most importantly, we need to understand effectiveness of various managerial decisions on the water system, since efficient policy making is the only viable solution for sustaining water sources and supply (reservoir) at any water-scarce region of the world.

We have developed a COupled WAter model (COWA) that is integrated with the human system and the earth system through bidirectional feedbacks. Policies are introduced as drivers of the model so that the effect of each policy on the system can be measured as we change its level. We have applied our model to a data-rich watershed in the United States: Phoenix AMA watershed, which is a dry region. The model is trained with the data from 1900–2010, and then projections are made for the next several decades. Historical data were recovered from the records at the US National Archives. We have also used remotely sensed satellite data in conjunction with data from local municipalities. Response of the system to six different short and long term policies are presented. We show that it is possible to guarantee the freshwater supply and sustain the freshwater sources through a proper set of policy choices for even a dry region.

4.1 Statement of the (regional, interstate, or multi-state) water problem

With a changing climate and intensified hydrological cycle, the importance of water resources is very likely to increase in the near future. Potential droughts, floods, and storms can have adverse impacts on availability of water supply for agricultural, industrial, and residential usages. We construct a minimal, Coupled Human-Climate-Water Model (COWA) in order to explore the effectiveness of different policies on mitigation of, as well as adaptation to, the water-related problems. In this paper, we apply the model to the Phoenix Active Management Area (AMA) Watershed Region (from here on, Phoenix Region) as a case study.

Water is a critical resource for use in energy production, agriculture, industry, and households. The imbalance between water availability and demand becomes larger as population and consumption rate grow. With the changing climate and the associated intensification of the hydrological cycle, we are likely to see more regions adversely affected by extreme precipitation events, and the Phoenix Region will not be an exception. Extreme climatic events can lead to several types of disasters, including droughts, floods, and storm surges. Each of these can endanger water quality and availability. Therefore, their potential damage to the water system needs to be studied.

Water shortage problems due to a drought may result in a regional conflict, even a humanitarian crisis, depending upon its severity. For example, the drought in Somalia has caused "the worst humanitarian disaster", as stated by the U.N. refugee agency [United Nations News Service, 2011]. At the domestic level, the serious water shortage in metro Atlanta has fueled a legal battle among Georgia, Alabama, and Florida over Lake Lanier water sharing [Feldman, 2008; Wortzel, 2009]. As another example of regional water shortage, the Potomac River Basin region has experienced two series of droughts, first 1930-32 and then 1958-71 [James, 2012]. The former drought caused major losses for agriculture in the area and severe shortage of food besides outbreak of epidemics and significant hardship due to shortage of water. Such crises show the importance of studying possible factors and options that can lead to more efficient water use and reuse practices.

Floods and storms, on the other hand, can not only seriously damage water infrastructure like pipelines, dams, and reservoirs, but can also deteriorate the quality of the freshwater resources. A domestic example is the flood in August 2010 in Ames, Iowa. This flood temporarily cut off about 55,000 people from drinking water due to pipe bursts. The local water and pollution control officials called for people to stop nonessential water use purposes, and fined those who did not comply. They also warned people about water contamination due to drainage and dropped pressure of the water towers [Crumb, 2010]. It is clear that flood consequences can be significantly minimized by investing on appropriate preventive measures such as infrastructure maintenance. Such investments would be also instrumental for quick recovery of the affected regions. Therefore, it is important to carefully study how floods and storms can affect the water supply with a model that realistically simulates the climate variability introduced by anthropogenic emissions and land use change, such as urbanization. Such studies should help in devising mitigation/adaptation water policies as well as strategies to deal with the aftermath of catastrophic events.

4.2 Nature, scope, objectives, and potential benefits of the project

Water-efficient technologies [Western Water, 2009], better pipe quality, water recycling [Bryck et al., 2008], and rooftop rainwater collection should all be very useful for sustaining the water supply. However, fully implementing all of these solutions requires a good deal of investment, which is unlikely to be available under current economic pressures. Also, the solutions may have different cost-to-benefit ratios in different regions. For example, if in a certain region the pipelines are in good condition, so that leakage is not a major concern, available funding might be better invested in building water recycling facilities. A major goal of this research is to find the efficiencies of different water-saving strategies under different climate scenarios. Such information is crucial for determining minimum required investment in various sectors of the water system that guarantees no sector can become the Achilles heel of the system during a catastrophe.

Computer models provide us with a powerful tool to simulate the outcomes under different sets of conditions. So far, few studies have used computer models to test the efficiency of different water policies. One example is a recent research on water use in South Florida, in which Ahmad and Prashar [2010] applied a complex system dynamics model to study certain factors in the regional water management. Ahmad and Prashar used only the water levels in one lake from 1980-2005, so their results may not hold if the precipitation regime changes in future. Furthermore, a highly complex model with quite a few parameters requires a huge body of data for tuning that may not be available. Consequently, it may be difficult to replicate such work for another region. These potential shortcomings motivate us to establish a framework applicable to different regions, using a minimal, efficient model. Such a model provides an opportunity to carry out many series of experiments that can help to understand more efficient ways of conserving water resources.

We have built our coupled model with the following components: The UMD Earth System Model (ESM), is used to conduct an offline run for the Phoenix Region with the monthly observational datasets from the Climate Research Unit (CRU). The River-Routing Module (RRM) is developed and coupled with the UMD ESM. From the runoff output information for each model grid, total river inflow and outflow for PAMAWR is calculated. Then the simulated evaporation and river inflow and outflow rates are fed into COWA. By doing so, the efficiency of different water-conserving options can be evaluated. These options include migrating to water-efficient technologies, fixing pipeline leaks, increasing the water recycling capacity, and introducing long-term water withdrawal policies.

The Coupled Human-Water-Climate model will be verified with the available historic data for PAMAWR from several sources, including USGS National Water Information System, USGS Instantaneous Data Archive, and extracted data from the records available at the US National Archives. The results can help policymakers to choose priorities for adaptation/mitigation water policies that can lead to effective investment of limited funds. In our future works, we will explore the possibility of applying the model to other regions, such as the State of California, the Potomac River Basin, the Fertile Crescent (e.g., Iraq, Syria, Lebanon, and Jordan) and eastern Africa (e.g., Somalia) where water problems are crucial and there is little data available.

The goal of this research is to model and then study the effectiveness of different investment/policy factors in different sectors of the water system under a changing climatic, including extreme weather events. The parts of the water system to be studied include dispensing technologies, transfer infrastructure, and recycling facilities. We will also study long-term policies for withdrawal of water from water sources (both Groundwater and Surface Water).

4.3 Methods, procedures, and sources of data

To conduct this research, we coupled the UMD Earth System Model (ESM) and a River Routing Module (RRM) to the Coupled Human-Climate-Water model (COWA). The model framework is illustrated in Fig. 4.1. COWA studies various effects of the Human System on the Water Resources and Water Supplies. COWA considers demographic characteristics of the human system, such as population, growth rate, regional migration, and water demand per capita as well as the influence of human on the management of the water systems. By coupling the ESM and RRM to COWA, we can simulate future availability of water supplies under changing climate and water policies.

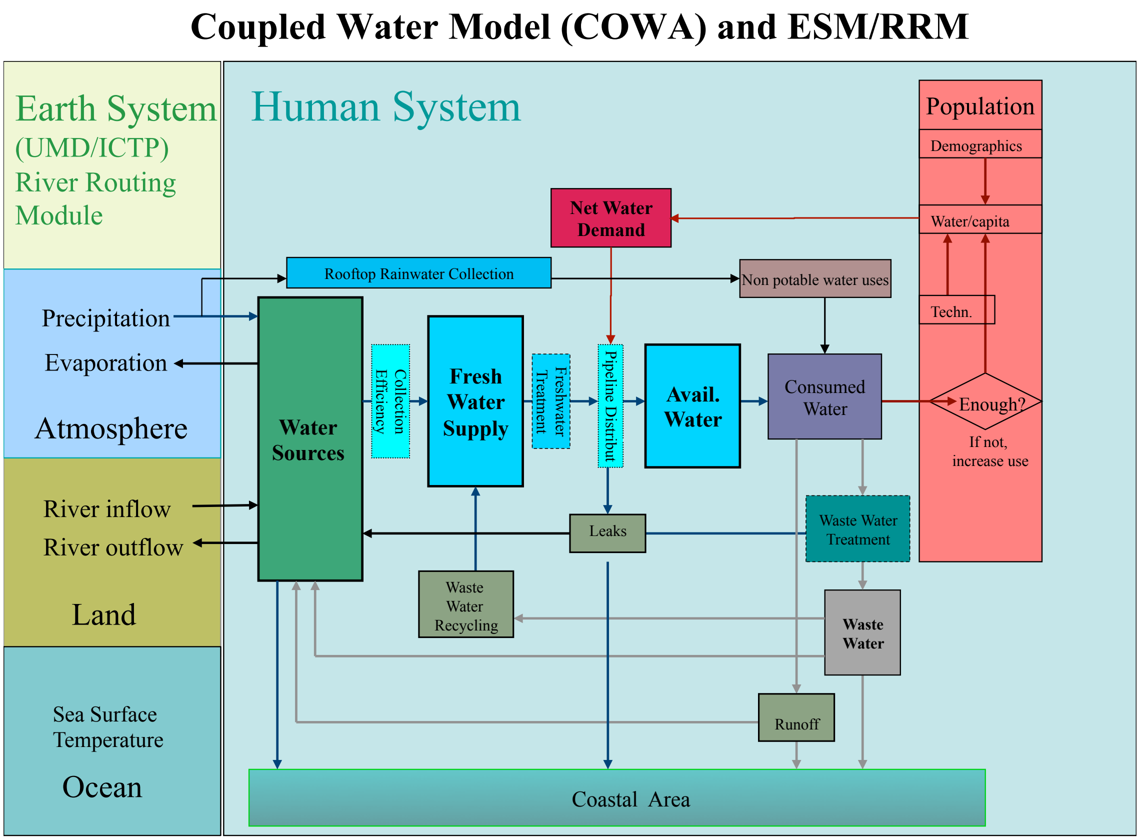

Figure 4.1: A schematic of the Coupled Water Model, including the Earth System Model (ESM) and the River Routing Module (RRM).

4.3.1 The UMD Earth System Model: Land and vegetation models

The UMD ESM includes a dynamic vegetation model (VEGAS), a simple land model (SLAND), and several other components. COWA requires as inputs precipitation, evaporation and river inflow and outflow rates in the region of study (in this case, PAMAWR). The river inflow and outflow rates are computed from the coupled River Routing Module, driven by runoff.

The land surface parameterization scheme is called Simple-Land (SLand). It has been built at an intermediate level of complexity to simulate the first-order effects of vegetation on climate variables. For simplicity, there is no diurnal cycle, and no environmental control on photosynthesis. Therefore, the soil moisture and seasonal variation of radiation are the main controlling factors. A single soil layer with different depth for the energy and the water balance is assumed. More information on energy balance and water budget equations can be found in Zeng et al. [2000]

The terrestrial carbon model VEgetation-Global-Atmosphere-Soil (VEGAS) simulates the dynamics of vegetation growth and competition among four different plant functional types (PFTs): broadleaf tree, needleleaf tree, cold grass, and warm grass. The different photosynthetic pathways are distinguished for C4 (warm grass) and C3 (the other three PFTs) plants. Phenology is dynamically simulated as the balance between growth and respiration/turnover. Competition is determined by climatic constraints as well as resource allocation strategies such as temperature tolerance and height-dependent shading. The relative competitive advantage then determines fractional coverage of each PFT with possibility of coexistence [Zeng et al., 2005; Zeng, 2003].

4.3.2 Environmental Drivers: Bias Correction and Summary

General Circulation Models (GCMs) are important tools in assessing climate change and in helping decision making to mitigate and adapt to future availability of water. However, there are inevitable model biases due to inadequate knowledge of key physical processes (e.g., cloud physics) and simplification of the natural heterogeneity of the climate system that exist at finer spatial scales. For example, substantial precipitation biases, especially in the tropics, are common in many models [Randall et al., 2007].

Traditionally, additive correction is often applied to correct the biases of model means, that is, to simply add the delta difference between a reference observation period and the model simulated mean future climatology:

$$\bar{C} = \bar{O} + M - \bar{M}, \tag{4.1}$$

where C is the corrected value, $\bar{O}$ is the observed climatology for the reference period, M is the simulated value, and $\bar{M}$ is the simulated climatology. For wet biases (model simulates higher precipitation climatology than observation), this method may result in negative rainfall, which is unphysical.

An alternative method is multiplicative correction [Sheffield et al., 2006]:

$$\bar{C} = \bar{O} + \frac{\bar{O}}{\bar{M}} \times (M - \bar{M}) \tag{4.2}$$

This method scales the perturbation with the ratio of observed to modeled climatology. A drawback for this method is when model has large dry bias, this correction could lead to unrealistically high rainfall.

To avoid the limitations of the two methods above, we implemented a Mixed Additive-Multiplicative (MAM) correction method to perform bias correction using rainfall observation from the latest global gridded Climate Research Unit (CRU) TS3.21 dataset. We chose 1961-1990 as the reference period for climatology:

$$\bar{C} = \begin{cases} \bar{O} + M - \bar{M}, & \text{when} \quad \dfrac{\bar{O}}{\bar{M}} \geq 1 \\ \bar{O} + \dfrac{\bar{O}}{\bar{M}} \times (M - \bar{M}), & \text{when} \quad \dfrac{\bar{O}}{\bar{M}} < 1 \end{cases} \tag{4.3}$$

As a simple combination of two popular methods, we believe MAM correction is a conceptually intuitive, easy to implement, yet effective bias correction method.

To create the monthly rainfall scenario for PAMAWR, we chose a representative ensemble member of the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) RCP4.5 output. This model is a participant in the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase 5 (CMIP5). We retrieved the simulated rainfall from the Earth System Grid Federation (ESGF), an international network of distributed climate data servers [Williams et al., 2011]. Then we applied the MAM method to create a combined (1901-2012 CRU and 2013-2100 CCSM) rainfall monthly time series for the AMA watershed from 1901-2100.

Similarly, for monthly evaporation losses, we combined the simulated results from the UMD ESM and the CCSM output for PAMAWR with the MAM method.

4.3.3 River-Routing Module (RRM)

Based on the principles in Miller et al. [1994], similar to the concept of the Total Runoff Integrating Pathways (TRIP) developed by Oki and Sud [1998], we developed a river routing module (RRM) that routes runoff based on river channel characteristics in the Global Dominant River Tracing (DRT) based Hydrography Datasets. The recently developed DRT algorithms utilize information on global and local drainage patterns from baseline fine scale hydrography inputs to determine upscaled flow directions and other critical variables including upscaled basin area, basin shape and river lengths. It preserves the original baseline hierarchical drainage structure by tracing each entire flow path from headwater to river mouth at fine scale while prioritizing successively higher order basins and rivers for tracing [Wu et al., 2011, 2012]. We use the 0.5 degree version of flow direction, flow and river channel slope from the DRT dataset as input to the River Routing Module. We followed the equations in Miller et al. [1994] for computing river flows, specifically, the equations are as below.

The rate at which water leaves a grid box, F, mainly depends on the water storage above the sill depth, S, the flow distance between the grid boxes, d, and topography gradient.

$$F = S \cdot \frac{u}{d} \tag{4.4}$$

In Eq. (4.4), F ($\mathrm{Kg \cdot m^{-2} \cdot s^{-1}}$) is the river flow flux to the downstream grid; S ($\mathrm{kg \cdot m^{-2}}$)

represents the free-flowing mass of water (lakes, rivers, and groundwater) above the sill depth in each grid; d (m) is the meandering flow distance from the DRT dataset distance (we use the minimum of the meandering flow distance from DRT dataset and the shortest distance between current and its downstream grid); and u (m·s^{-1}) is an effective flow speed of water from a grid box to its downstream neighbor.

The value of u depends on local characteristics of the river basin, such as its morphology and topography gradient:

$$u = 0.35\,(i/i_0)^{1/2}, \tag{4.5}$$

where i is the river channel slope from the DRT dataset and $i_0 = 0.004$ (median value of the DRT dataset) is the reference topography gradient we use. We limit u within a realistic range of 0.15 – 5 m/s. An upper limit on u is necessary to prevent numerical instabilities in the river routing model. Minimum u is used when the downstream grid is at a higher elevation than upstream.

Changes in water storage at each grid box is given by:

$$\frac{dS}{dt} = R + \sum F_{IN} - F_{OUT}, \tag{4.6}$$

where F_{OUT} is the rate at which river mass leaves a grid box, $\sum F_{IN}$ is the sum of the water flux entering a grid from all of its neighbors, and R represents the runoff from the UMD model. At each time step, after computing the river outflow at grid X, we add it to the inflow of its downstream grid, Y (if Y is also a land grid). Thus river inflow at every grid is calculated after looping through all grids.

We found this simple river routing scheme captures a realistic global river flow pattern, and we believe it is suitable for the purpose of this study, where we simply sum up river flow entering and exiting PAMAWR each month from 1900-2010.

We assume river inflow and outflow in future shows similar characteristics as the historical period, and we simply repeat the river inflow and outflow time series from our River Routing Model as the future river flows for AMA watershed. Admittedly this is a simple treatment, however, given the purpose of this conceptual study, and the large uncertainty in evaporation and river flow simulations, we believe the scenario we used in our study is plausible.

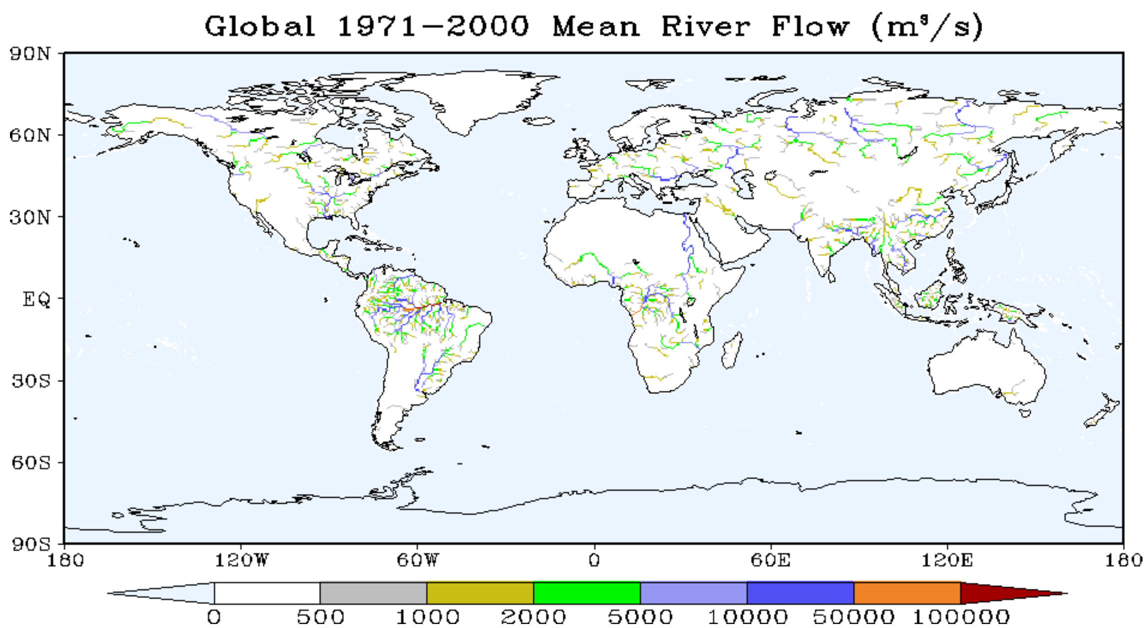

Figure 4.2: Global mean river flow from 1971 to 2000.

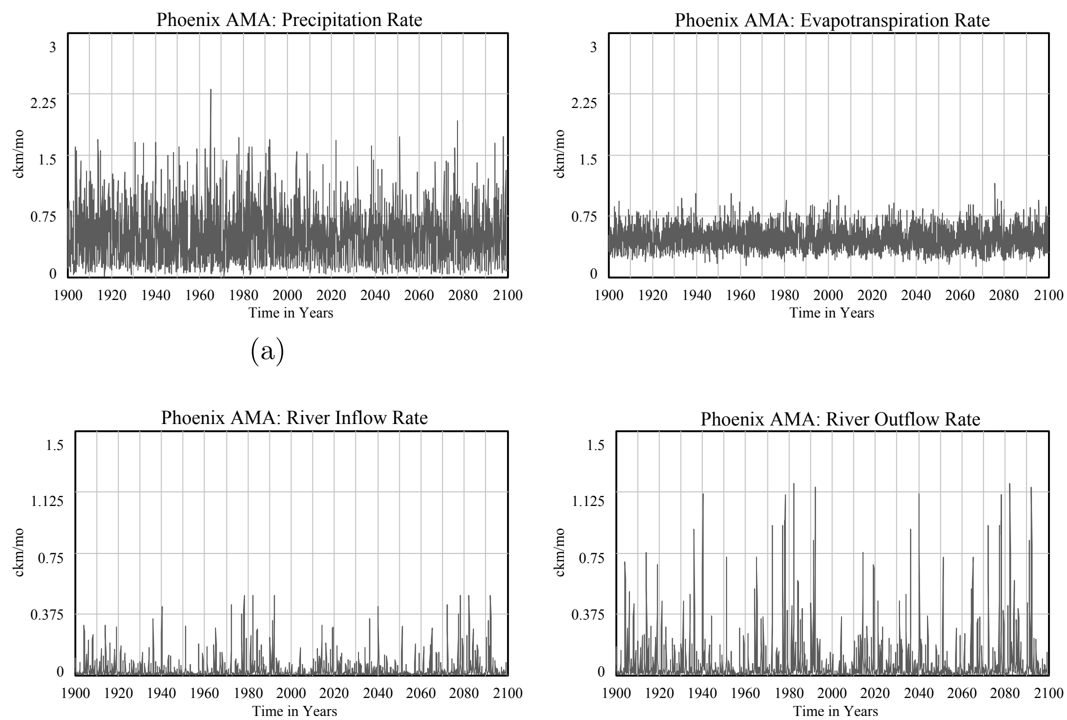

Figure 4.3: Time Series of monthly precipitation, evaporation, and river inflow and outflow for PAMAWR from 1900 to 2100.

4.3.4 Sources of Data

Sources of data for this work include Bryck et al. [2008]; James [2012]; Kenny et al. [2009]; Solley et al. [1998]; Western Water [2009], as well as the following online open-access resources:

- FAO AQUASTAT: http://www.fao.org/nr/water/aquastat/main/index.stm
- FAO Country Profiles: http://www.fao.org/countryprofiles/en/
- Great Lakes Information Network: http://www.great-lakes.net/
- National Groundwater Association Groundwater facts: http://www.ngwa.org/gwscience/ground_water_use/faqs.aspx

- NCDC (National Climatic Data Center, U.S. Dept of Commerce) and NOAA Satellite and Information Service: http://www.ncdc.noaa.gov/oa/ncdc.html
- United States Geological Survey Instantaneous Data Archive: http://ida.water.usgs.gov/ida/
- United States Geological Survey Earth Resources Observation and Science (EROS) Center: http://eros.usgs.gov/publications
- HYDRO1K Database: https://lta.cr.usgs.gov/HYDRO1K
- United States Geological Survey National Water Information System: http://waterdata.usgs.gov/nwis

4.4 COWA

COWA (COupled WAter model) is a minimal model for the human-water system. COWA is coupled to a Global Climate Model (GCM) and a River Routing Module (RRM). COWA itself has only four stocks: Population, Surface Water Sources, Groundwater Sources, and Freshwater Supply. In this version of COWA, consumption of water by different sectors of the economy and society is combined into a single flow, *Consumption*. A main feature of COWA is that Population is endogenously coupled to the water system through bi-directional feedbacks. This coupling can produce results that would be otherwise be impossible to obtain if population is treated as an exogenous variable.

One can use COWA to run *"thought experiments"* on the lifetime of Sources/Supply under various assumptions for recycling capacity, pipeline leakage, and dispensing technology.There are certain parameters in the model that are determined through policies. Therefore, effects of various policies can be studied with COWA.

The four state variables in COWA are Population, x, Surface Water Sources, y_S, Groundwater Sources, y_G and (stored) Freshwater Supply, z. Population is controlled by the death rate, α, birth rate, β, and immigration rate, I. Death rate is not a constant but increases as consumption per capita decreases beneath a threshold value. Immigration rate is not a constant either. It is proportional to the consumption per capita, and becomes negative as consumption drops below a certain threshold. Surface water stock is controlled by several flows: river inflow, Φ, river outflow, Ψ, precipitation, P, evapotranspiration, E, withdrawal of water from surface water sources into the supply, W_S, groundwater recharge, G, leak to sources, Λ, flow of non-recycled water to sources, N, and runoff to sources, Ω. Groundwater stock, on the other hand, has only one incoming flow, groundwater recharge, G, and one outgoing flow, withdrawal of groundwater into the supply, W_G. Freshwater supply is controlled by three inflows, withdrawals, $W_S + W_G$, and recycling, R, and two outflows, supply collection, K, and leakage, L. Rooftop collection rate, Γ, is directly available for consumption and therefore, is deducted from the total precipitation when calculating net inflow of water to (surface water) sources.

While P, E, Γ, Φ, and Ψ are exogenous variables (or time series) for COWA, W_G, W_S, K, R, L, Λ, Ω, N, and Σ are all functions of other model parameters and variables. Model parameters are demand per capita, δ, technology factor, τ, transfer efficiency, η, assurance factor, θ, maximum withdrawal capacity, W_M, maximum groundwater withdrawal rate, W_{GM}, maximum recycling capacity, R_M, and maximum capacity of supply, z_M. There are also three coefficients which are bounded between 0 and 1: consumptive to sewer, σ, runoff to sources, ω, and non-recycled to sources, ν. It is assumed that leaked water returns to sources with a time delay λ.

Total demand, $\Delta(t)$ is given by:

$$\Delta(t) = \delta x(t). \tag{4.7}$$

Effective demand is given by the total demand divided by the technology factor:

$$D(t) = \frac{\Delta(t)}{\tau} = \frac{\delta}{\tau} x(t). \tag{4.8}$$

It can be seen that $\tau = 1$ represents the base technology, $\tau > 1$ indicates a water saving technology, and $\tau < 1$ refers to an inefficient water dispensing technology. Transfer efficiency, η, is defined through the equation:

$$K(t) = \eta\big(K(t) + L(t)\big). \tag{4.9}$$

This equation essentially shows that only a factor η of the total water withdrawn from the freshwater *supply*, $K + L$, is consumed and the rest is wasted through leaks. Therefore, leakage rate and consumption rate are directly related through η:

$$L(t) = \frac{1-\eta}{\eta} K(t). \tag{4.10}$$

Net water that is available for recycling is the sum of the consumption to sewer rate, $\Sigma(t) = \sigma(K(t)+\Gamma(t))$. Flows that determine the Supply level, i.e., (two) withdrawals, consumption, leakage, and recycling can then be expressed as follows:

$$\begin{cases} W_S(t) &= \min\left(\theta_S \dfrac{y_S}{\Delta t}, \theta_O \dfrac{z_M - z}{\Delta t}, W_{SM}\right) \times \min\left(1, \dfrac{y_S}{nD}\right) \\ W_G(t) &= \min\left(\theta_G \dfrac{y_G}{\Delta t}, \theta_O \dfrac{z_M - z}{\Delta t}, W_{GM}\right) \times \min\left(1, \dfrac{y_G}{nD}\right) \\ K(t) &= \max\left(0, \min\left(D(t), \theta_K \eta \dfrac{z(t)}{\Delta t}\right) - \Gamma\right) \\ L(t) &= \dfrac{1-\eta}{\eta} K(t) \\ R(t) &= \min\left(\theta_O \dfrac{z_M - z}{\Delta t}, \Sigma(t), R_M\right) \end{cases} \tag{4.11}$$

The consumed water that does not go to sewer, $(1-\sigma)(K+\Gamma)$, flows to runoff and a portion of it, Ω, goes to sources. Moreover, a portion of the water that has gone into the sewer but has not been recycled, N, goes back to the sources. These three flows are therefore defined by:

$$\begin{cases} \Lambda(t) &= L(t-\lambda) \\ \Omega(t) &= \omega(1-\sigma)(K(t)+\Gamma(t)) \\ N(t) &= \nu\left(\Sigma(t)-R(t)\right) \\ \Sigma(t) &= \sigma\left(K(t)+\Gamma(t)\right) \end{cases} \tag{4.12}$$

Now that we have defined all the components, we can write the equations governing COWA:

$$\begin{cases} \dot{x} &= \beta x - \alpha x + I(t) \\ \dot{y}_S &= \Phi(t) + P(t) - \Psi(t) - E(t) - W(t) + \Omega(t) + \Lambda(t) + N(t) - G(t) \\ \dot{y}_G &= G(t) - W_G(t) \\ \dot{z} &= W_S(t) + W_G(t) + R(t) - K(t) - L(t) \end{cases} \tag{4.13}$$

A schematic of the variables of COWA and their connections to the ESM and RRM is shown in Fig. 4.4.

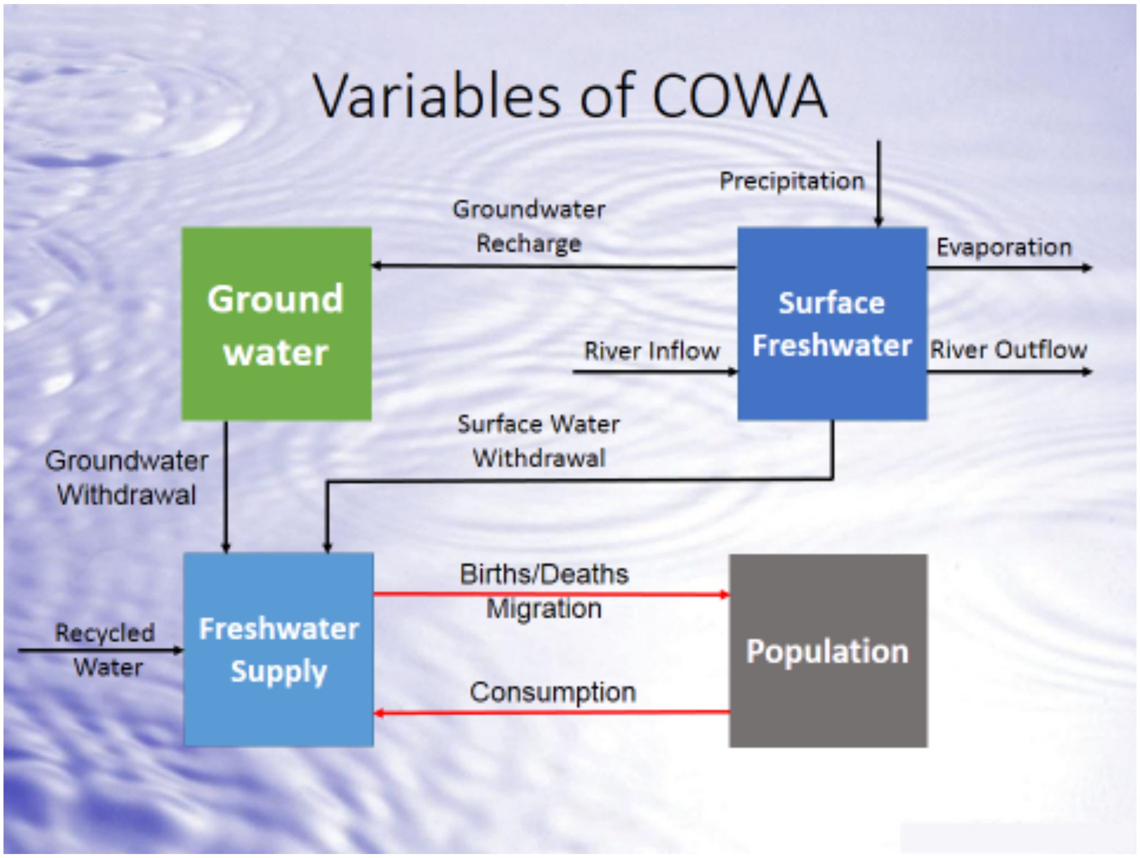

Figure 4.4: A schematic of the state variables of COWA, including the flows among them as well as the linkages to ESM and RRM. Red arrows show feedbacks while black arrows show flow of water.

Below we will present definitions for variables, parameters, and functions used in COWA in three tables:

Table 4.1: State Variables (Stocks) used in COWA

Variable Symbol	Variable Name	Governing Equation
x	Population	$\dot{x} = \beta x - \alpha x + I$
y_S	Surface Water Sources	$\dot{y}_S = P - E + \Phi - \Psi - W_S + \Lambda + \Omega + N - G$
y_G	Groundwater Sources	$\dot{y}_G = G - W_G$
z	Freshwater Supply	$\dot{z} = W_S + W_G + R - K - L$

Table 4.2: Definition of Functions used in COWA Equations

Function Symbol	Function Name	Describing Equation
P	Precipitation rate	Exogenous
E	Evapotranspiration rate	Exogenous
Φ	Net River Inflow rate	Exogenous
Ψ	Net River Outflow rate	Exogenous
Γ	Rooftop Collection rate	Exogenous
I	Immigration rate	$= I_b\Big(\frac{C}{C_{th}} - 1\Big)$
G	Groundwater Recharge rate	$= \max\big(0, f(P-E)\big)$
W_S	Surface Water Withdrawal rate	$= \min\Big(\theta_S \frac{y_S}{\Delta t}, \theta_O \frac{z_M - z}{\Delta t}, W_{SM}\Big) \times \min\Big(1, \frac{y_S}{nD}\Big)$
W_G	Groundwater Withdrawal rate	$= \min\Big(\theta_G \frac{y_G}{\Delta t}, \theta_O \frac{z_M - z}{\Delta t}, W_{GM}\Big) \times \min\Big(1, \frac{y_G}{nD}\Big)$
K	Rate of Collection from Supply	$= \max\Big(0, \min\big(D, \theta_K \eta \frac{z}{\Delta t}\big) - \Gamma\Big)$
L	Leakage rate	$= \frac{1-\eta}{\eta} K$
R	Recycled Water rate	$= \min\Big(\theta_O \frac{z_M - z}{\Delta t}, \Sigma, R_M\Big)$
Δ	Total Demand	$= \delta x$
D	Effective Demand	$= \Delta/\tau$
C	Consumption per Capita	$= (K+\Gamma)/x$
C_{th}	Threshold Consumption per Capita	$= \mu(\delta/\tau)$
α	Death rate	$= \max\big(\alpha_M - (\alpha_M - \alpha_m)(C/C_{th}), \alpha_M\big)$
Λ	Leak to Sources	$= L(t-\lambda)$
Ω	Runoff to Sources rate	$= \omega(1-\sigma)(K+\Gamma)$
N	Nonrecycled to Sources rate	$= \nu(\Sigma - R)$
Σ	Consumptive to Sewer rate	$= \sigma(K+\Gamma)$

Table 4.3: Description of Parameters used in COWA

Parameter Symbol	Parameter Name
α_m	Normal (Minimum) Death rate
α_M	Famine (Maximum) Death rate
β	Birth rate
I_b	Base Immigration rate
δ	Demand per Capita
μ	Threshold Consumption per Capita ratio
η	Transfer Efficiency
τ	Technology factor
z_M	Maximum Capacity of Freshwater Supply
W_{SM}	Maximum Surface Water Withdrawal rate
W_{GM}	Maximum Groundwater Withdrawal rate
R_M	Maximum Recycling Capacity
$n_{S,G}$	Number of Reserve Months (Long-term Policy) for Surface Water and Groundwater
f	Infiltration rate
$\theta_{S,G,K,O}$	Assurance factor (Short-term Policy) for Surface/Ground Water Withdrawal, Collection from Supply, and Supply Overflow
μ	Threshold Consumption per Capita ratio
λ	Leak to Sources Time Delay
ω	Runoff to Sources ratio
ν	Nonrecycled to Sources ratio
σ	Consumptive to Sewer ratio

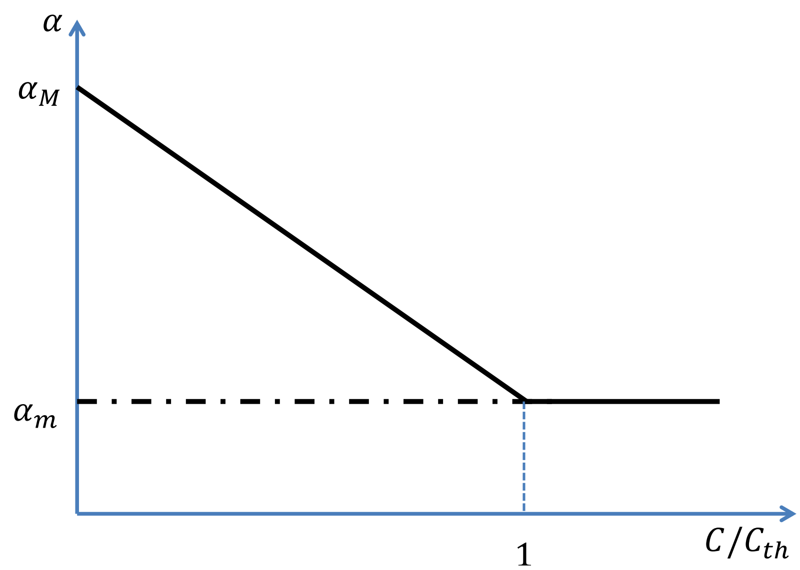

Figure 4.5: Death rate as a function of consumption per capita and demand per capita. Note that C_{th} is directly proportional to δ.

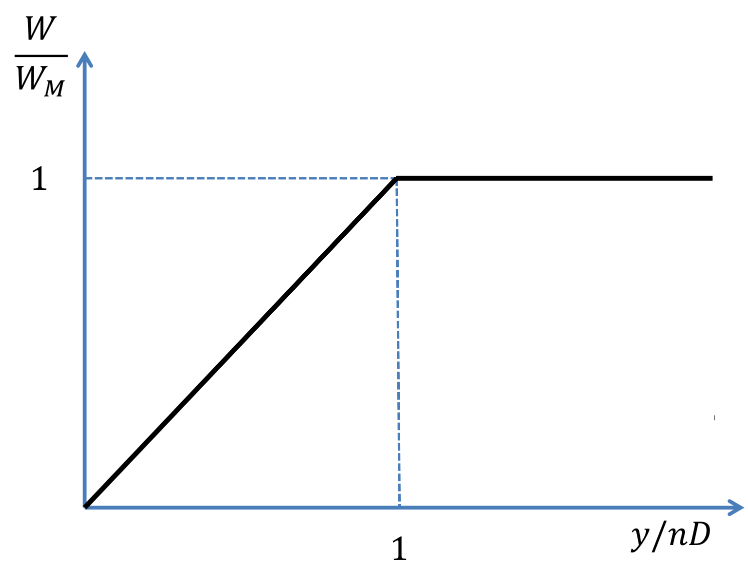

Figure 4.6: Withdrawal rate as a function of available freshwater sources, y, effective demand, D, and number of reserve months, n. The latter parameter is a strong policy knob that can have important implication for sustaining water sources. By choosing a large n, we can insure long-term availability of water, however, it implies a mandatory reduced consumption for the short-term in the event of a drought.

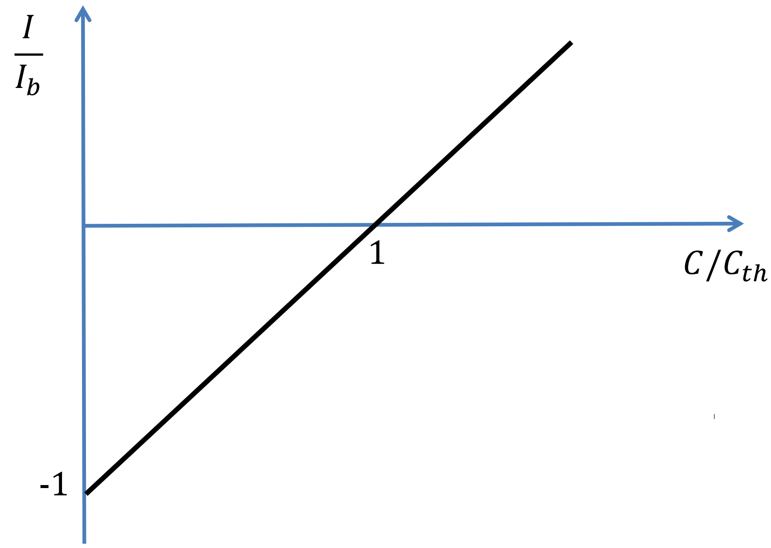

Figure 4.7: Immigration rate as a function of consumption per capita. While consumption is above its threshold level, there is immigration into the region. However, when it drops below the threshold value, people start to emigrate from the region.

4.5 Application to the Phoenix AMA Watershed

Scenarios to be studied are due to changes of R_M, τ, η, z_m, $y_{G,i}$, n, and θ.

4.5.1 Base Run

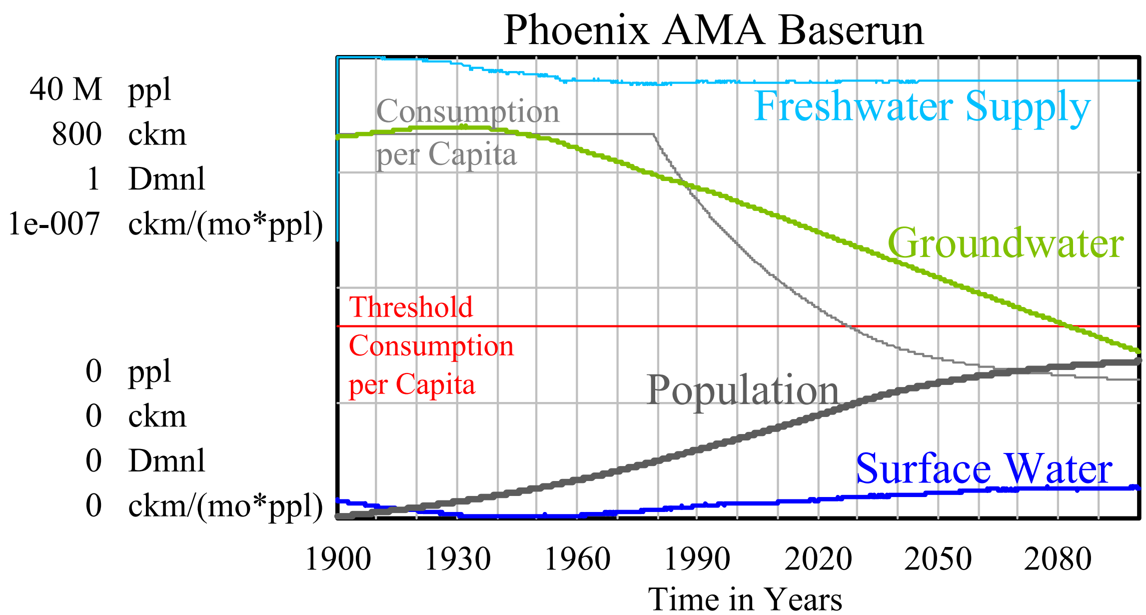

Figure 4.8: Base run for the Phoenix AMA Watershed.

The following parameter values and initial conditions are used for the base run: Normal death rate $\alpha_m = 0.0006$, normal birth rate $\beta = 0.0016$, initial population $x_i = 27,000$, initial groundwater $y_{G,i} = 660$, initial surface water $y_{S,i} = 30$, initial supply $z_i = 3$, total reservoir capacity $z_M = 5$, surface water withdrawal capacity $W_{SM} = 1$, groundwater withdrawal capacity $W_{GM} = 1$, surface water reserve months $n_S = 60$, groundwater reserve months $n_G = 60$, recycling capacity $R_M = 0$, transfer efficiency $\eta = 0.85$, technology factor $\tau = 1$, base immigration $I_b = 3,000$, demand per capita $\delta = 8.3?10^{-8}$. Time step is 1 month (mo); Unit of volume is cubic kilometer (ckm); Unit of population is people (ppl). Freshwater Supply z is shown normalized to z_M in all the figures. Units for all the other quantities are chosen to conform with the basic units mo, ppl, and ckm. Base run can give us a basis for comparing the impact of different water management options and policies.

4.5.2 Addition of Recycling

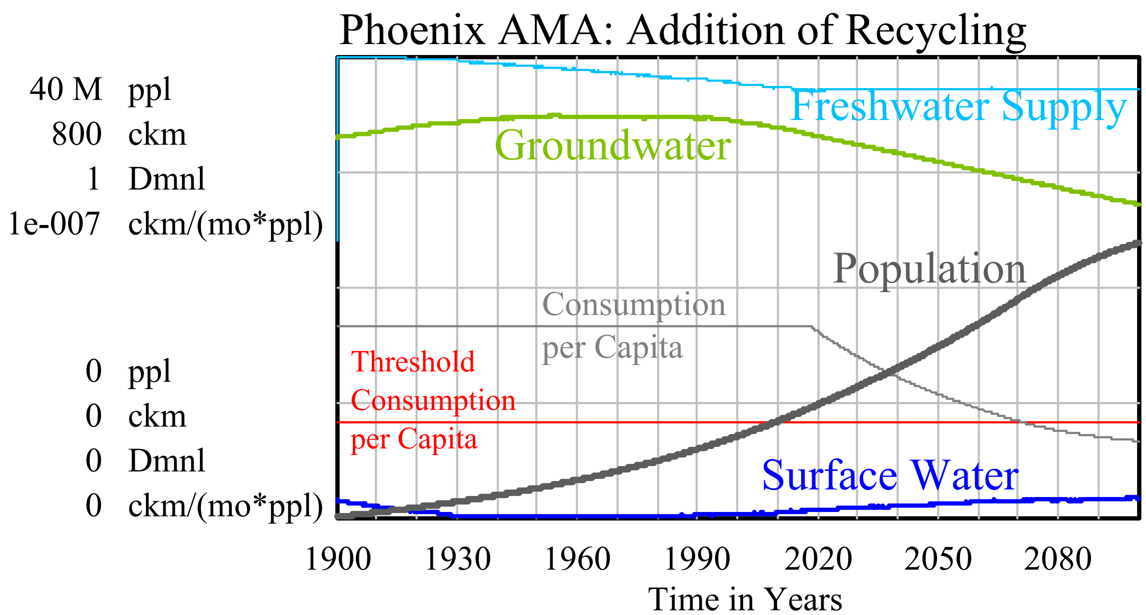

Figure 4.9: Addition of recycling to the base run for the Phoenix AMA Watershed.

By adding a recycling capacity R_M of 1 ckm/mo, final population can grow to a maximum of 23M, compared to 14M without recycling. More importantly, groundwater ends up at a level of 550 ckm, compared to 300 ckm, which is a significant improvement.

4.5.3 Improvement in Technology

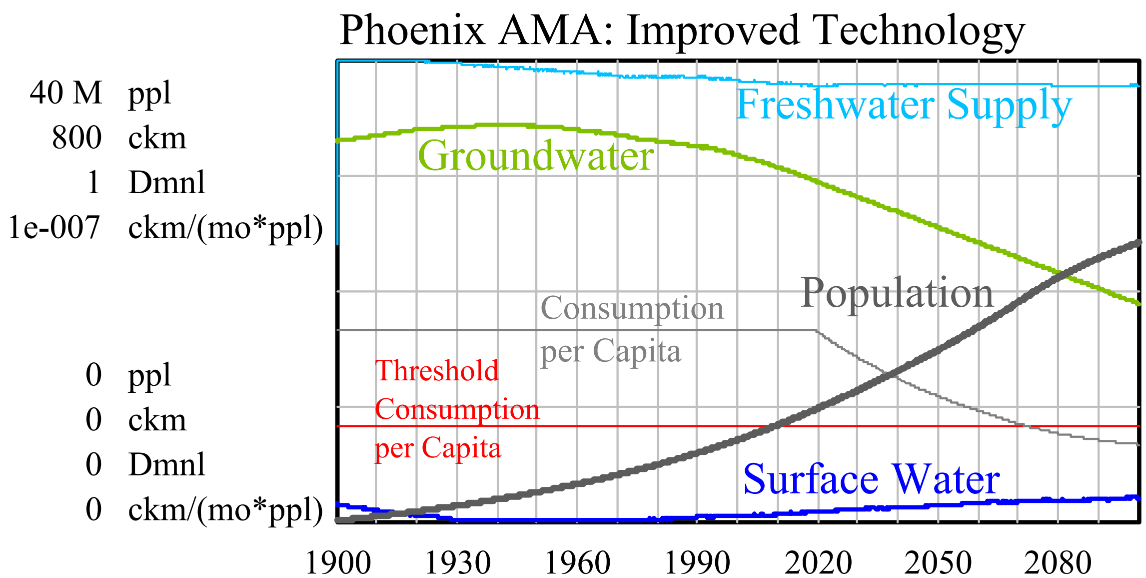

Figure 4.10: Improvement in technology of the base run for the Phoenix AMA Watershed.

By increasing the technology factor to $\tau = 2$ (equivalent to reducing effective demand by half), population can grow to a maximum of 24M, compared to 14M with no technology improvements. More importantly, groundwater ends up at a level of 490 ckm, compared to 300 ckm.

4.5.4 Againg vs. Improved Pipelines

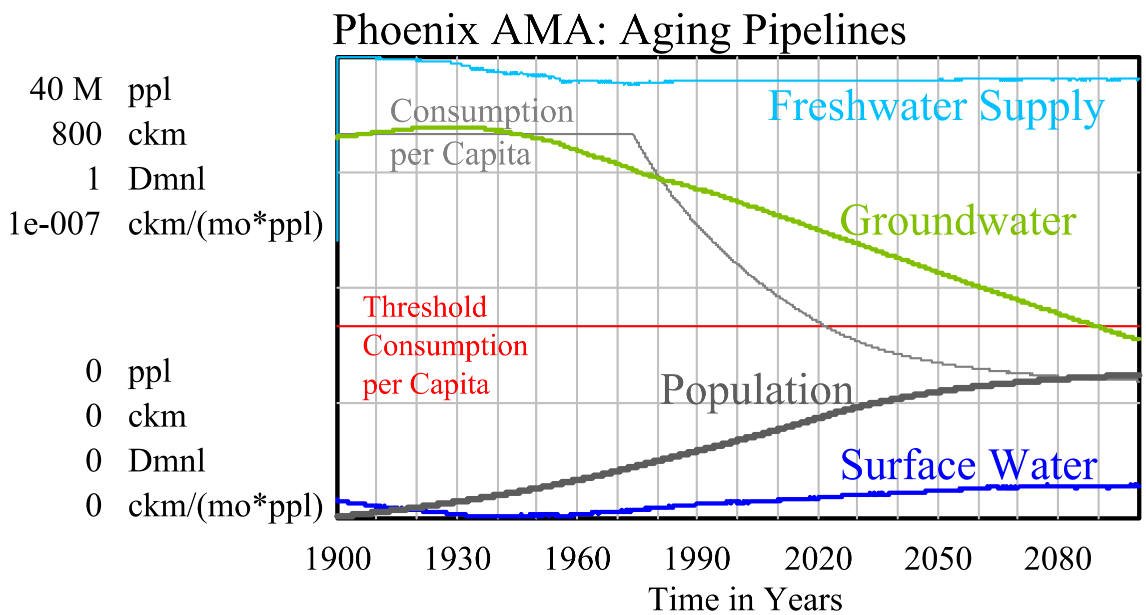

Figure 4.11: Aging pipelines for the Phoenix AMA Watershed.

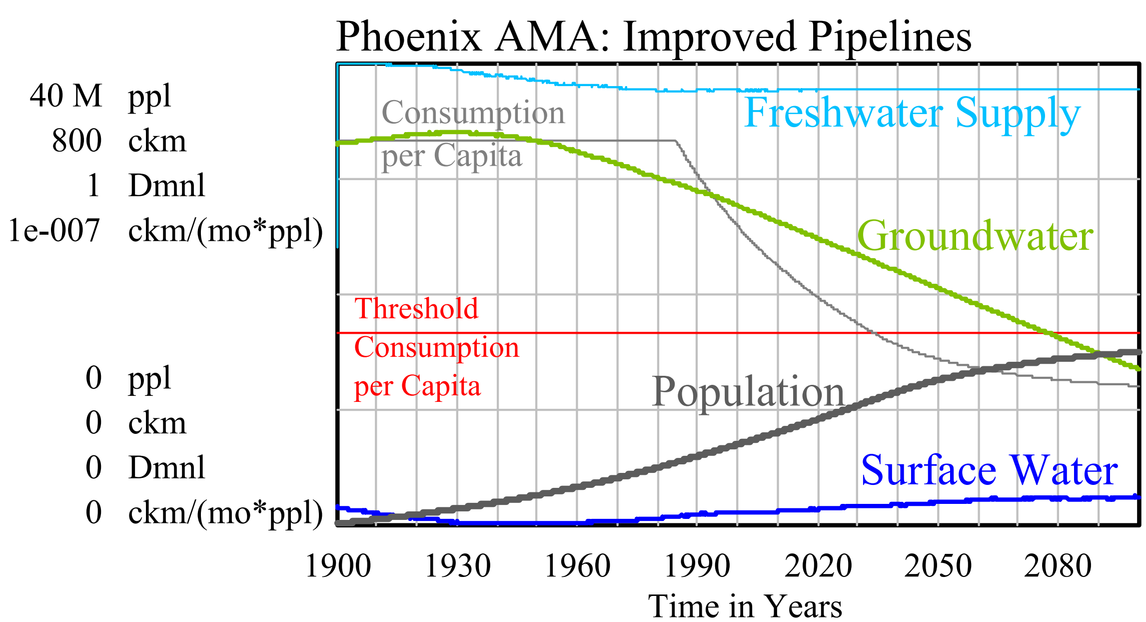

Figure 4.12: Improved pipelines for the Phoenix AMA Watershed.

By reducing the leaks 10% ($\eta = 0.95$ to $\eta = 0.95$), final population increases to 15M, compared to 14M. The impact on groundwater is small.

4.5.5 Higher Reservoir Capacity

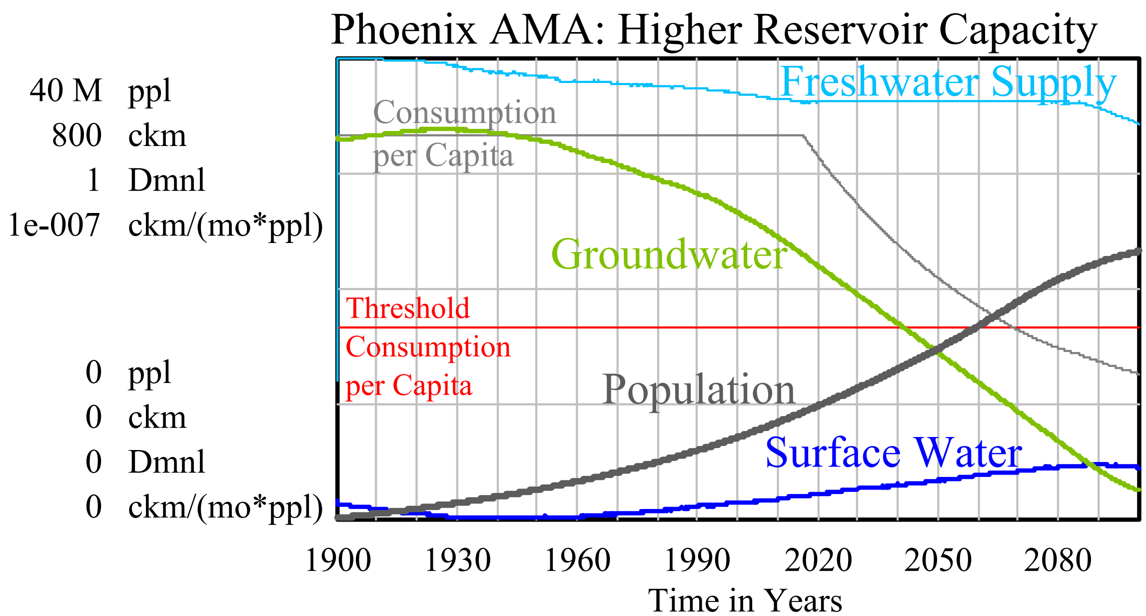

Figure 4.13: Higher reservoir capacity for the Phoenix AMA Watershed.

By doubling the reservoir capacity to $z_M = 10$, population can grow to a maximum of 23M, compared to 14M. However, groundwater ends up at a very low level of 50 ckm. Stricter groundwater withdrawal policies can improve this.

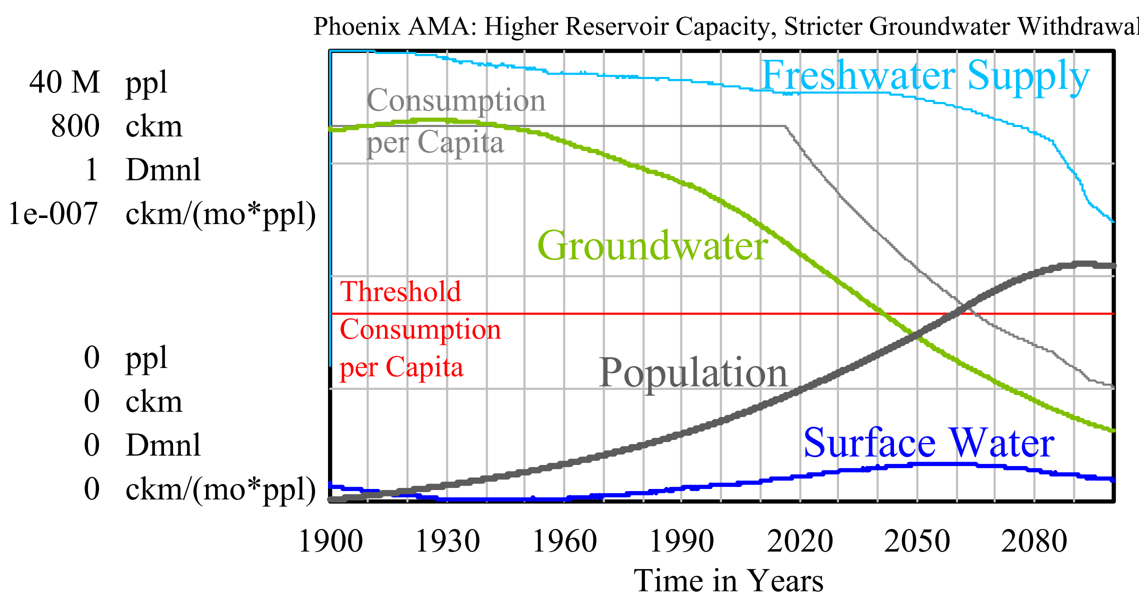

Figure 4.14: Higher reservoir capacity with a stricter groundwater withdrawal policy for the Phoenix AMA Watershed.

The reservoir capacity is doubled to $z_M = 10$, but at the same time, groundwater reserve months is increased from $n_G = 60$ to $n_G = 300$. Population grows to a final level of 21M instead of 23M. However, groundwater ends up at a level of 140 ckm, which is much better than 50ckm, reached when no changes in groundwater withdrawal policy are implemented.

4.5.6 Uncertainty in Groundwater Estimates

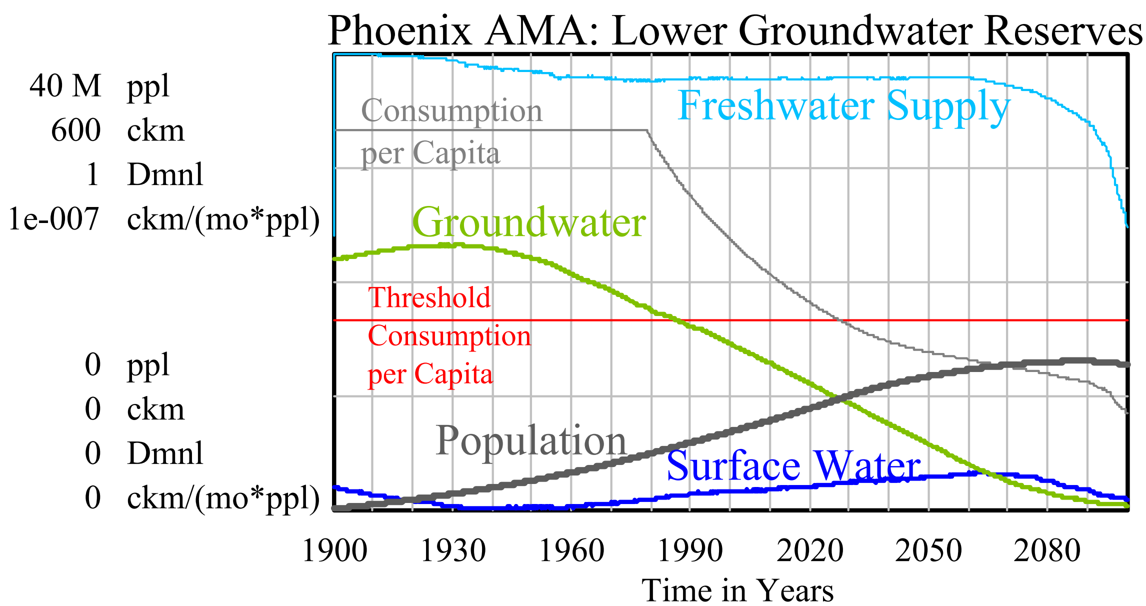

Figure 4.15: Uncertainty in groundwater estimates for the Phoenix AMA Watershed.

With a 50% error in the estimate of the total groundwater, population could grow to a maximum of 13M, compared to 14M. However, groundwater ends up at a much lower level of 5 ckm, which is unacceptable. Stricter groundwater withdrawal policies could prevent this.

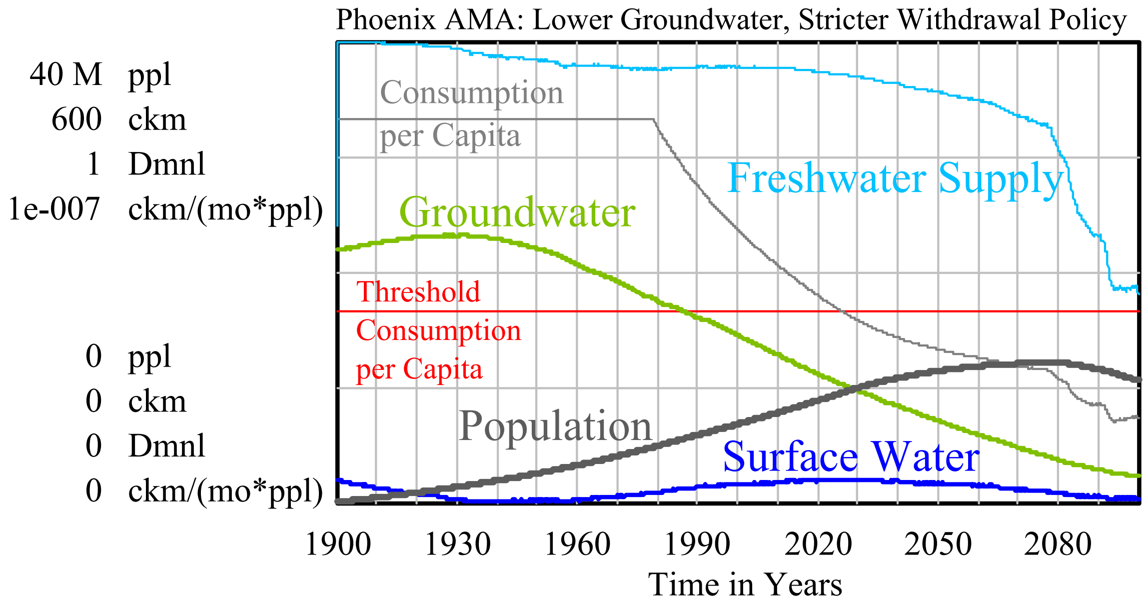

Figure 4.16: Stricter groundwater withdrawal policy for the Phoenix AMA Watershed when there is uncertainty in groundwater estimates.

The initial groundwater is reduced to $y_{G,i} = 330$, but at the same time, groundwater reserve months is increased from $n_G = 60$ to $n_G = 300$. Population grows to a final level of 10M instead of 13M. However, groundwater ends up at a level of 40 ckm, which is much better than 5 ckm, reached when no changes in groundwater withdrawal policy are implemented.

4.6 Summary

Our main focus in this work is on the societal, economic, management, and policy implications of the results from the coupled human-water-climate model. Ahmad and Prashar [2010] developed a complex water model addressing economic and management issues for the water system in southern Florida. Our goals are similar to those of Ahmad and Prashar, but we have added some modules and simplified others, which may have advantages for water decision-making. Since Ahmad and Prashars model does not include a climate model or a river routing module, it makes it difficult to assess issues arising from precipitation regime changes and more extreme events. Moreover, their model is very complex and requires much data that may not be available for most regions. The complexity of the model makes it difficult to communicate the results to the public, or the policy-makers with little or no technical background. In short, our model combines several components involved in the water cycle in a simple, efficient, novel model whose potential outcomes are significant. Nevertheless, COWA can only be considered as a "thought-experiment" model to guide decision making due to its minimal structure.

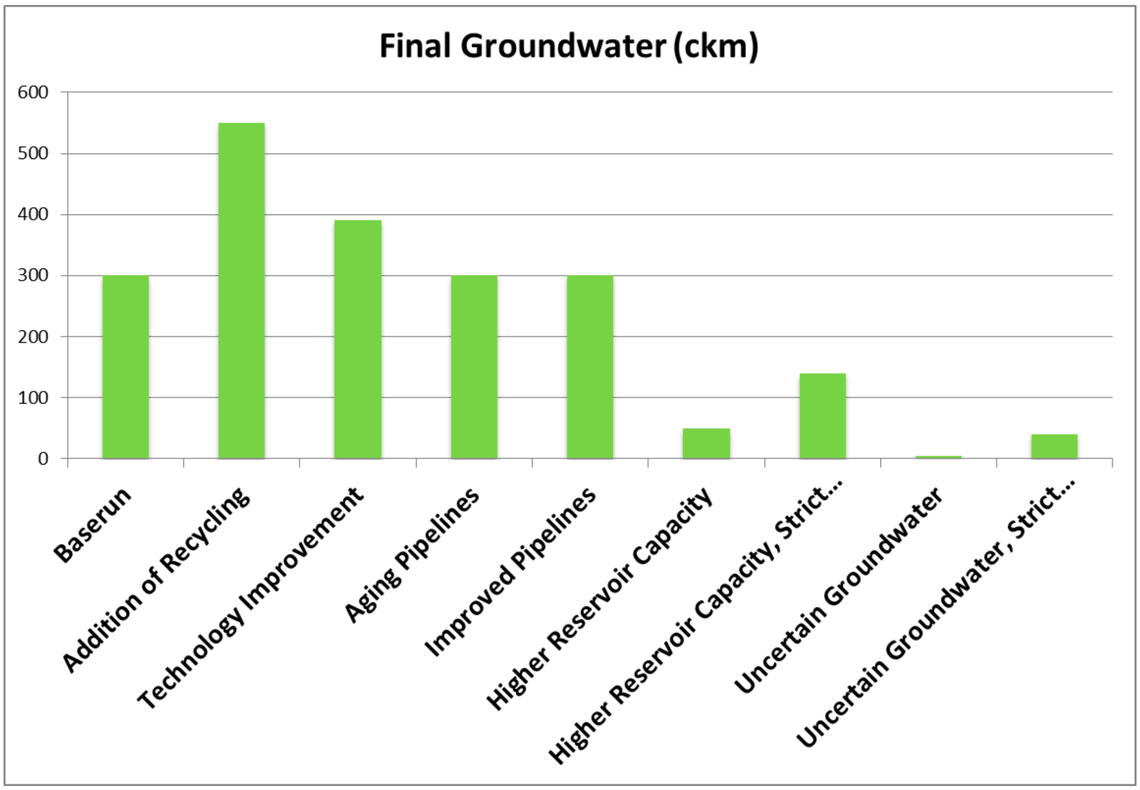

Figure 4.17: Summary of the final level of groundwater from different scenarios for the Pheonix AMA Watershed.

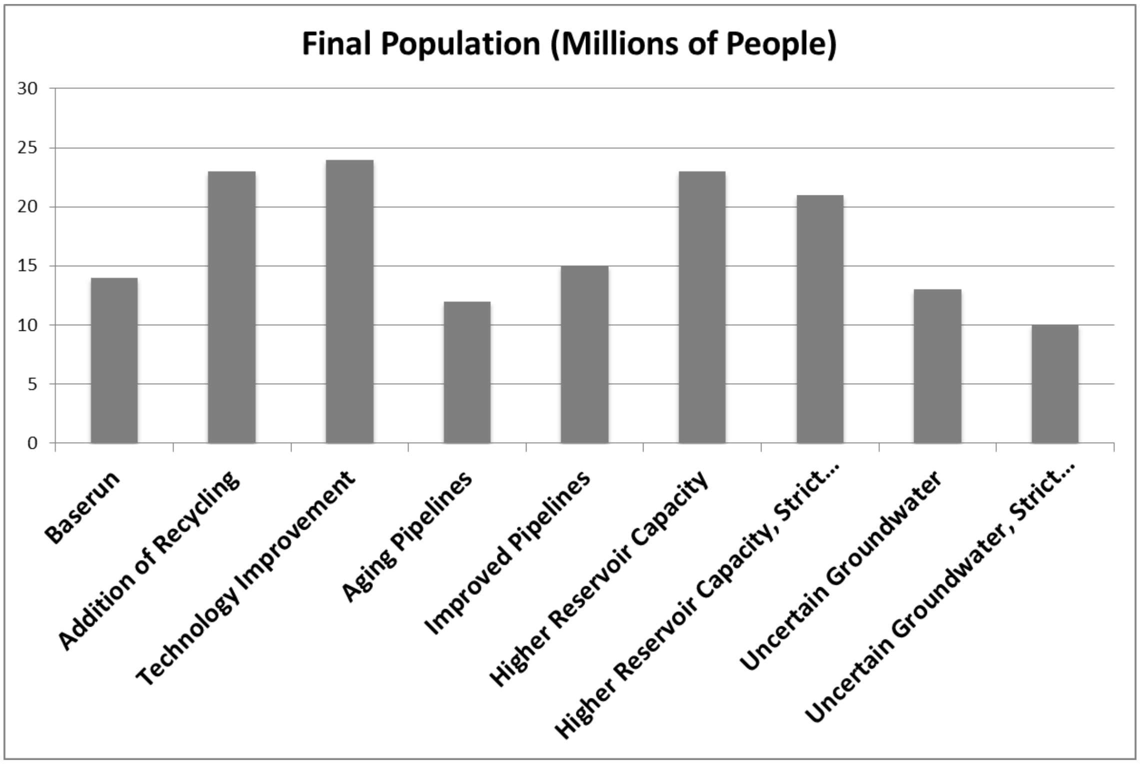

Figure 4.18: Summary of the final level of groundwater from different scenarios for the Pheonix AMA Watershed.

Figs. 4.17 and 4.18 give a summary of the results from various scenarios presented above. Improvements of recycling and dispensing technology are essential for both increasing the "water carrying capacity" of population and conserving water sources. Higher reservoir capacity can increase the Water Carrying Capacity of population, but can lead to dangerous depletion of water sources in the absence of strict withdrawal policies. Such policies are also essential when estimates of water sources are uncertain. We can also have regional development policies in place which discourage immigration into the region of a particular watershed whenever population reaches the level of Water Carrying Capacity.

Long term impacts of water management options such as recycling, technology, transfer infrastructure, and reservoir capacity can be tested. But it is essential to include bidirectional coupling of water with population.It is important to have long term policies for water reserves. An economic module will be developed and integrated into the human-water model in order to assess economic feasibility and efficiency of each policy, and the impact on population and the natural system.

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