This is to certify that the
dissertation entitled

Taking A Systems Approach to Risk Assessment and
Disaster Recovery: The Case of Montserrat

presented by

Jack Lewis Rozdilsky

has been accepted towards fulfillment
of the requirements for the

Doctoral degree in Resource Development - Urban Stud

G. Schultz.

Major Professor's Signature

June 7, 2005

Date

Doctoral Dissertation

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TAKING A SYSTEMS APPROACH TO RISK ASSESSMENT AND DISASTER RECOVERY: THE MONTSERRAT CASE

VOLUME I

By

Jack Lewis Rozdilsky

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Resource Development and Urban Studies

2005

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ABSTRACT

TAKING A SYSTEMS APPROACH TO RISK ASSESSMENT AND DISASTER RECOVERY: THE MONTSERRAT CASE

By

Jack Lewis Rozdilsky

In 1995, the Soufrière Hills volcano began to erupt on the Eastern Caribbean island of Montserrat. Most of Montserrat's urban centers located on the southern two-thirds of the island were completely destroyed and over 60% of the island's population evacuated. Currently, all reconstruction is taking place in a zone of lesser volcanic risk on the northern one-third of the 39 ½ square mile island. In 2005, the island's population is approximately 4,690 people, new towns are beginning to be constructed in the north, and Montserrat is struggling to recover as the volcano remains active. During the early stages of recovery, a goal was set to reconstruct the island to a level of development that can support 10,000 people, the approximate pre-crisis level.

This study asks the question "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 persons feasible, given development constraints and continued risks?" In order to address that question the method of system dynamics modeling is applied. System dynamics modeling is based after the work of Forrester and it involves development of feedback models to analyze structural relationships that drive behavior over time. In this study, a Montserrat Urban and Risk Model is developed and simulated under four risk scenarios. The basis for the method of this study is urban dynamic modeling, and it is expanded on to include both geographic and risk components.

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Given the limitations of the model, it is suggested that the goal of 10,000 persons may be too high for Montserrat. By experimenting with the model under various risk circumstances, it was determined that a goal of reaching population levels of 6,500 to 7,500 people may be more feasible, given the island's limits. The model indicated that land fraction occupied is a main concern since as the island rebuilds and the population grows, nearly 100 % of the land becomes occupied during the next 35 years. It is suggested that policy steps be taken to limit development in order to reduce the land fraction occupied. That strategy would not limit future opportunities for redevelopment in the context of continued hazard risk.

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ACKNOWLEDGEMENTS

As this dissertation was a long and difficult process, I would like to acknowledge persons who have assisted me.

At Michigan State University (MSU), Dr. Gerhardus Schultink guided me to the end of this process, and I would like to thank him for his guidance and the contribution of ideas to this work. I also wish to recognize Dr. Ralph Levine and his generous contribution of time he has spent with me concerning the development of the system dynamics model, and his support of my academic pursuits in general. Dr. John Schweitezer and Dr. Jim Bingen also contributed to this work through their roles on my committee. In the Department of Resource Development, Dr. JoAnn Beckwith assisted with my literature review prior to her departure, and Dr. Peter Kakela supported my Montserrat research early in my Doctoral studies.

Also at MSU, I also want to acknowledge support from (the former) Urban Affairs Program, which greatly assisted me in completing this goal. I would also like to express appreciation to the Tri-County Regional Planning Commission and MSU Extension in helping me to facilitate the closure of this process.

Throughout my disaster research various persons on Montserrat and in the natural hazards research community provided much appreciated assistance.

I would also like to thank Deanna and other persons who have provided friendship during my studies in Michigan.

Lastly, I want to thank my parents for their support in ways to numerous to recount.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction To Dissertation

Approximately 500 to 700 natural disaster events are recorded each year. Only a few of these natural disasters are categorized as 'great' natural catastrophes that result in death or losses so high as to require outside assistance, according to Munich RE, a reinsurance firm which deals with catastrophic loss claims (Munich RE, 2000). During the past 50 years, there has been a dramatic increase in the number of catastrophic disasters. In the 1950s, there were 20 'great' catastrophes. In the 1970s, there were 47, and in the 1990s there were 86 (Abramovitz, 1990). The December 26, 2004, earthquake of magnitude 9.0 at the Sumatra-Andaman Islands illustrates the extent to which natural catastrophes are an ever-present threat. While the earthquake was measured as the fourth largest since 1900, the subsequent tsunami caused one of the worst disasters in the last century with more than 283,100 people killed[1] (United States Geological Survey, 2005). A need exists for better understanding the process of recovery from natural disasters.

One of the 'great' natural catastrophes of the late-1990s was the volcanic eruptions on Montserrat, British West Indies. Montserrat is an island territory located in the Leeward Island group of the Lesser Antilles in the Caribbean Sea. After hundreds of years with no volcanic activity of significance, the volcano began an eruptive period in 1995. By 1996, the disaster quickly overwhelmed the response capabilities of the small

[1] In addition to severe damage and casualties caused by the earthquake in northern Sumatra, Indonesia, and the Nicobar Islands, India, the tsunami caused more casualties than any other in recorded history. As reported during March 2005, disaster recovery is taking place across 10 countries in South Asia and East Africa. More than 283,100 people were killed, 14,100 are still missing, and 1,126,900 were displaced by the catastrophe (United States Geological Survey 2005).

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island, forcing massive evacuations and numerous aid packages from the British Commonwealth and overseas donors. While most of the devastation took place from 1996 to 1998, the volcano still remains active at the time of writing. A 2003 observation of the crisis states, "To date, the eruption continues unabated, thereby prolonging one of the longest-duration volcano crises in the world" (Komorowski and Tilling, 2003).

1.2 Montserrat and the Volcanic Disaster

The Montserrat volcanic crisis was chosen for study, because it illustrates one of the few situations of direct impacts of volcanoes on cities during the Twentieth Century. In considering how society can develop strategies for dealing with the hazards that volcanoes represent to cities, it has been suggested that after determining vulnerability of a city due to volcanic hazards, public officials must develop long-term risk mitigation strategies through appropriate land use planning, zoning and building codes, and the development and practice of contingency plans (Miller, 2001). Long-term recovery planning in response to Montserrat's volcanic disaster involves the abandonment of the existing urban areas and the creation of new towns in areas with lesser volcanic risk.

Most of the development on Montserrat took place on the southern two-thirds of the island, in close proximity to what was thought to be an extinct volcano. The land area of the island is 39 ½ square miles and the 1991 population (prior to the volcanic crisis) was 10,400 persons (Physical Planning Unit, 1999).

In August of 1995, with the venting of ash clouds and explosions at the volcano, it became clear that a larger eruption was imminent. Prior to the 1995 events, no eruptions of that magnitude had been observed on Montserrat since Europeans arrived in the

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Caribbean. Unfortunately, as much of the development on Montserrat had taken place in close proximity to the volcano, as volcanic activity dramatically increased in 1996 and 1997, the disaster was catastrophic to human settlements on Montserrat. The sheer level of destruction was unprecedented as the island's major cities, including the capital city were destroyed. During the eruption, much of the population fled under emergency conditions. It was reported that as few as 2,850 people remained on Montserrat during the height of the crisis (Development Unit, 2001). During the Twentieth Century, few places have experienced the sheer levels of physical destruction and social dislocation faced by Montserrat.

Disaster recovery on Montserrat involves completely rebuilding all aspects of life in zones of lesser volcanic risk. The northern one-third of the island has been designated as a safe zone. New towns are being created from scratch to house the population and replace the urban functions that were destroyed by the volcano. While volcanic activity has somewhat diminished, the volcano still remains active. During the past few years, the boundaries between safe and unsafe zones have been set and areas for new development have been designated. As the island rebuilds in the northern safe zone, the 2005 population is 4,690 persons (Government of Montserrat, 2005).

A target approach to development planning on the island has been adopted based on attracting people back to the island and encouraging population growth. An overall target of 10,000 persons equates to the on-island population prior to the onset of volcanic activity and is considered by the government of Montserrat to be realistic in terms of the carrying capacity of the northern part of the island (Physical Planning Unit, 1999).

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1.3 The Research Problem - Can Montserrat Reach Its Redevelopment Goal?

The primary research problem is, "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 persons feasible, given development constraints and continued risks?"

In defining the existence of a problem, Ackoff establishes five necessary conditions (Ackoff, 1962):

1) An individual or decision maker who has the problem
2) The outcome that is desired by the decision maker (i.e., an objective)
3) At least two unequally efficient courses of action which have some chance of yielding the desired objective
4) A state of doubt in the decision maker as to which course is best
5) An environment or context of the problem

While many problems can be considerably more complex than the minimal conditions needed to describe a scientific problem as outlined above, the above steps can assist in defining the nature of a problem.

In conceptualizing the problem of Montserrat's disaster recovery, we can first consider the individual or decision maker who has the problem. In this case, the problem is not in the realm of the individual, but a group of individuals, represented by a government entity with an interest in sustainable disaster recovery. This study will assume a single 'decision maker' that is a governmental entity which has the ability to make policy influencing Montserrat's disaster recovery.

The outcome that is desired by the decision maker, or the objective, is to reach a development goal of restoring the island's population to approximately 10,000 people (or the pre-crisis population) subject to development constraints and continued risk conditions. Given, the situation on Montserrat, this outcome will need to be achieved by a phased repatriation of the population and the consequent construction of facilities neede

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needed to support that population.

The third aspect of defining a problem is at least two unequally efficient courses of action which have some chance of yielding the desired objective. Ackoff (1962) stresses that for a problem to exist, there must be a real difference between the choices available to the decision maker. There are various strategies by which the island's population can be restored to 10,000 persons. For this study, a model will be developed and simulated under different risk conditions. Output from the simulations will help to determine policies for long-term disaster recovery.

The condition of a state of doubt in decision making is apparent with the case. As the situation of Montserrat's disaster is unprecedented, it is difficult to foresee all of the possible interactions that may either contribute to or detract from the redevelopment goal. While development goals have been stated, this author suggests that it is an open question as to whether such goals can be met. It should be noted that this question is not meant to imply doubts about current development activity on Montserrat. Maintaining human settlements while moving forward with post-disaster planning on an island with an active volcano has been a very difficult task which has demonstrated both the resiliency of Montserrat's governmental entities and its citizenry. However, this author would agree with statements made by one of the pioneers in urban dynamics modeling who, when considering the dynamics of cities in the northeastern United States, argued "Evolutionary processes have not given us the mental skill needed to properly interpret the dynamic behavior of systems of which we have now become a part"(Forrester, 1969).

The environment or context of the problem is the volcanic disaster recovery on Montserrat. However, applications of this work may also apply to other cases of catas

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catastrophic disasters where urban areas are destroyed and the nature of the disaster makes it necessary to shift population to safe zones and create new cities, as the risks remain too high to rebuild on the sites which were devastated.

In addition to the primary research question, secondary questions are related to exploring the implications of various policy scenarios that be can implemented to repatriate approximately 5,500 persons to the island (given that approximately 4,500 persons are now on the island). Such questions will be explored by investigating the capacity of the island to absorb the new population in terms of a Montserrat Urban and Risk Model.

To make this study unique, urban dynamics modeling methods will be expanded on by adding spatial and risk components relevant to the case of Montserrat. Assumptions will be made that different zones (within the safe zone) have different degrees of risk. That is, development areas closer to the volcano will have a greater risk. This study will illustrate how the Monstserrat Urban and Risk Model acts under scenarios of varied risk.

Output from quantitative modeling will be able to provide data which can be applied to answer the question of "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 persons feasible, given development constraints and continued risks?"

1.4 The Research Method – System Dynamics Modeling

The research method for this study will be system dynamics modeling. Within the context of systems science and systems thinking, system dynamics is a very specific type of modeling method that is based on the work of Jay W. Forrester. Forrester first

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introduced system dynamics modeling in his 1961 book *Industrial Dynamics*, in which he defined system dynamics as:

> "The investigation of the information-feedback characteristics of (managed) systems and the use of models for the design of improved organizational form and guiding policy"(Forrester, 1961).

System dynamics models are most effectively used for the general purposes of broad policy making and design for aggregate systems (Meadows & Robinson, 1985). The models are comparatively simple to understand and contain only top-level details of the systems being simulated. A main practical application of system dynamics modeling is that it can be used to conduct and evaluate policy experiments in an environment which is free of having real-life consequences (Kelly, 1998).

System dynamics models have four benefits in analyzing societal problems: 1) feedback loops are seen as the underlying structure of dynamics of behavior; 2) feedback loops have been identified as responsible for the counterintuitive behavior and policy resistance observed in real social systems; 3) feedback loops provide an intuitive and accessible description of mathematical models created to study the behavior of complex systems; 4) feedback loops enable the creation of self-contained theory where patterns of dynamic behavior are understood as consequences of the internal structure of causally closed loops (Richardson, 1991).

In this study, the system dynamics model will be especially useful as it allows for push and pull factors to be considered. One example of push and pull factors is the, "so-called urban push factors - the principal reasons why people are motivated to leave urban areas and the rural pull factors - the principal reasons why people are attracted to rural areas"(Schultink & Winoto, 1996). A key point to this study is that push and pull factors will

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will act to bring people to or drive people off the island. The system dynamics modeling method will permit for the analysis of the push and pull factors.

In investigating the research question, alternate approaches to system dynamics modeling could include other forms or geo-spatial analysis. In the case of Montserrat, built-out type analysis may be used to estimate the maximum amount of development that could occur under the existing land use controls. However, large amounts geospatial data would need to be created from scratch to complete such an analysis.

1.5 The Need for a Systems-Based Approach to Hazard Research

Strategies for managing hazards have often followed traditional planning models; that is study the problem, implement the solution, and move on to the next problem (Mileti, 1999). Despite the continued application of the traditional, linear models for managing hazards, disaster losses are rising as the world is becoming increasingly complex and interconnected.

In the recent second natural hazard assessment, *Disasters by Design: A Reassessment of Natural Hazards in the United States*, one of the suggestions was that:

> "Hazards researchers and practitioners would do well to take a more systems-based approach to understanding the complex interactions between the natural environment and human perceptions, actions (including what people build and where it is located), and organizations"(Mileti, 1999).

Mileti goes on to describe this systematic approach to the problem as focusing on interactions among system elements and on the effects of its interactions. In addition, a systematic approach examines a variety of factors, as well as integrating time, feedback, and uncertainty. This study suggests a need for a systems approach to hazard and risk reduction.

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1.6 Research Assumptions and Limitations

The limitations to this study are defined by the application of the system dynamics modeling method. The system is a group of functionally interrelated elements forming a complex whole (Sterman, 2000). However, a limitation of the model is that it is not designed to model the entire physical or social system of Montserrat during the disaster recovery. The usefulness of the model lies in the fact that it simplifies reality and creates a representation of it that can be understood. A truly comprehensive model would be just as complex as the system itself and just as inscrutable (Sterman, 2000).

In this study, assumptions are made to define the key variables in the model. Information gathered from primary source documents and relevant literature will be applied in assigning values to the variables. The key variables studied in the Montserrat Urban and Risk Model are related to land use and risk.

While the model considered economic factors through variables concerning business structures and jobs, it did not consider the amount of British development aid that is supporting life on the island. This study assumes that overseas aid to Montserrat will remain at level adequate to support the redevelopment of the island.

Also, it is important to note that when it is possible, system dynamics modeling would take place as an interactive process between the modeler and the client. In this study, while information from the situation on Montserrat informs the model, the model is not being created through an interactive process with persons on Montserrat.

Additional information concerning the assumptions made in this study is detailed in Chapter 5 and the Appendix.

1.7 Organization of the Study

Chapter Two provides a background on the Montserrat case. Information is provided concerning the island of Montserrat, the volcanic disaster itself, and elements of post-disaster uncertainty. Chapter Two provides information to inform the analysis.

Chapter Three provides the literature review. Relevant literature will incorporate elements of the hazard and risk assessment paradigms. The concept of disaster will be discussed, hazards and hazard research will be described, and risk will be discussed in the context of hazard. Chapter Three provides the conceptual foundations for this study's approach to disasters, hazards, and risk reduction.

Chapter Four is the methods chapter. After a background discussion on systems thinking and systems science, the system dynamics method will be described. Key elements of system dynamics, based on the work of Forrester, will be highlighted. As an introduction to the modeling methods, a simple model of population dynamics will be presented.

Chapter Five both depicts and describes the Montserrat Urban and Risk Model. The basic urban dynamics model on which the model is based is described. Also, adaptations to the urban in terms of geography and risk will be described. The Appendix will provide detailed definitions of the model.

Chapter Six is describes the risk scenarios that are simulated in the Montserrat Urban and Risk Model and provides the output from the model runs. Specific scenarios risk scenarios will be described and the initial comments on the results of the model run will be provided. Highlights of the model's output under various scenarios will be prov

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provided in Chapter Six and full reports of the model's output are provided in the Appendix.

Chapter Seven provides an analytical review of the results of the model runs. Highlights of the model runs are isolated and a discussion on the meaning of the models output is provided.

The final chapter, Chapter Eight is the research summary, recommendations and conclusions. Based on the scenarios considered, the question of "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 persons feasible, given development constraints and continued risks?" is answered by stating that 10,000 persons may be an overly optimistic goal. The study will conclude with comments on applications of the model beyond the Montserrat case, comments on possible areas of expansion for the model, and future research needs.

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CHAPTER TWO

THE MONTSERRAT VOLCANIC DISASTER

2.1 Introduction

The circumstances of the Montserrat volcanic disaster are adopted as the real-life situation on which this study is based. The purpose of this chapter is to provide a context for understanding Montserrat's volcanic disaster. The island is described along with its primary natural hazard, the Soufrière Hills Volcano. As the volcano is the root cause of the Montserrat disaster, some background is provided concerning the basic geological forces behind the eruptions. After describing the volcano itself, the volcano disaster and its impacts are described by addressing selected aspects of economic, social, and physical planning uncertainty created by the crisis. In conclusion, one aspect of the crisis is detailed, regarding how the disaster may be considered as a permanent feature of Montserrat's landscape by officials of the United States Government.

2.2 Why Montserrat Was Chosen for Study

During the time I was completing the doctoral program, the Montserrat volcano erupted. I began to investigate the Montserrat volcanic crisis in 1997. During, pre-dissertation research, I was able to draw initial conclusions concerning the disaster recovery on Montserrat.

After a February 2001 presentation of initial findings at the Cities and Volcanoes 2 Conference (Rozdilsky, 2001) in Auckland, New Zealand, I was able to discuss the Montserrat situation with other presenters involved in both response to volcanic hazards and scientific study of volcanoes. Comments were made concerning the uniqueness of

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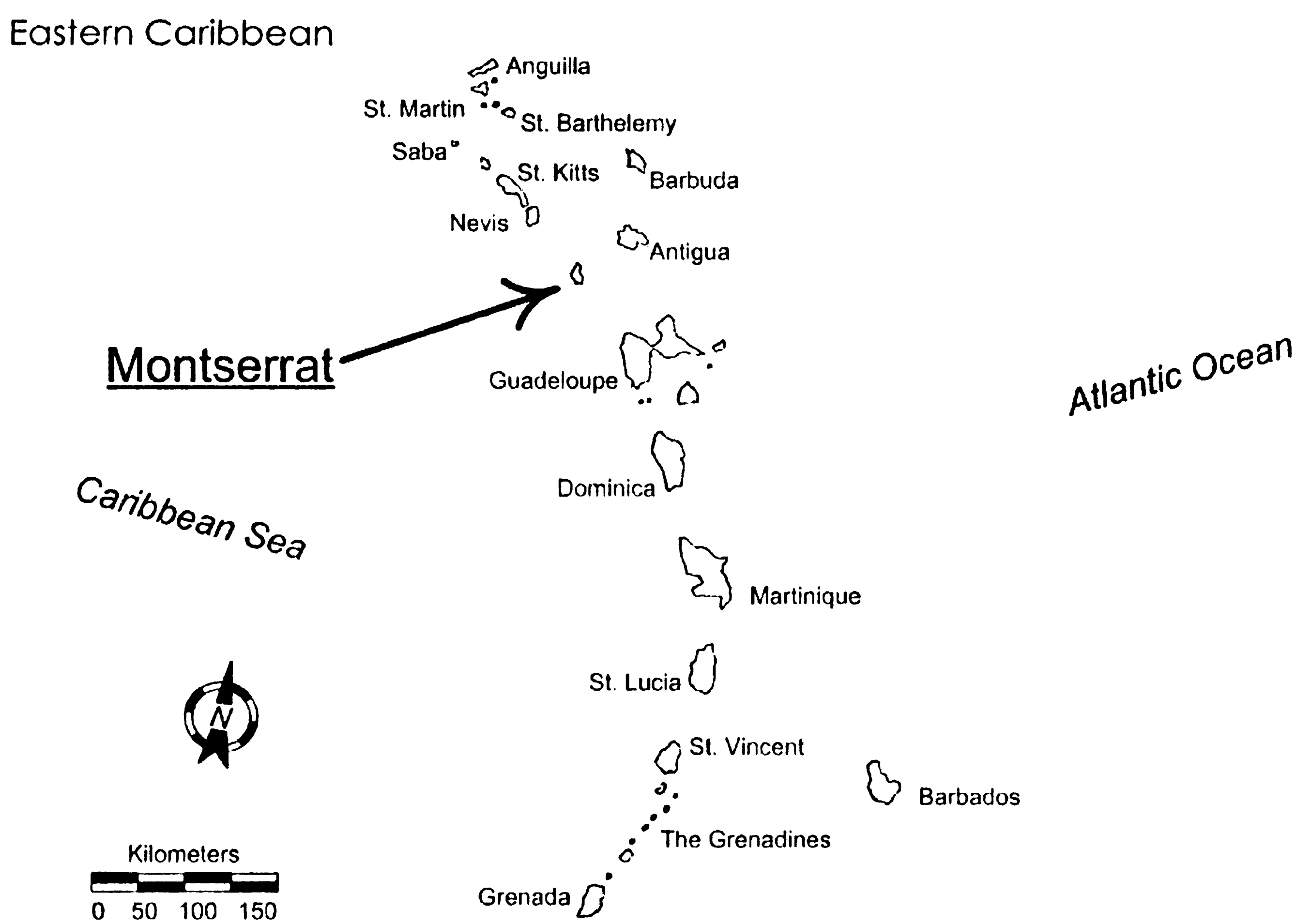
the Montserrat volcanic crisis, since these types of crises are few and far between. Due to the long-term geological time frames in which eruptions occur, there are few opportunities to study eruptions during a given lifetime. The Montserrat volcanic crisis has been illustrative of one of the few direct interactions between human settlements and volcanoes during the Twentieth century.

In addition to other small island states, Naples, Italy, a few cities in Central America and Indonesia, and Auckland, New Zealand face serious volcanic risk. In considering how society can develop strategies for dealing with the hazards that volcanoes represent to cities, it has been suggested that after determining vulnerability of a city due to volcanic hazards, public officials must develop long-term risk mitigation strategies through appropriate land use planning, zoning and building codes, and the development and practice of contingency plans (Miller, 2001) .

While the frequency of these volcanic disasters is low, if the disaster occurs it will likely be catastrophic. Long-term contingency planning for responding to these disasters will likely involved abandonment of existing urban area and creation of new urban areas in zones of lesser volcanic risk. The study of Montserrat's experiences provides a body of knowledge to assist in future post-disaster planning efforts.

2.3 Montserrat, British West Indies

Montserrat is an island territory located in the inner arc of the Leeward Island group in the Lesser Antilles of the Caribbean Sea, located 25 miles southwest of Antigua (see Figure 1). Physically, the island is volcanic in origin and the terrain is dominated by



Adapted from Map in: Hudson, B. (1989). The commonwealth eastern Caribbean. In R. B. Potter (Ed.), *Urbanization, planning, and development in the Caribbean* (pp. viii, 327 p.). New York: Mansell.

Figure 1. Location of Montserrat in the Eastern Caribbean

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extinct volcanoes[2], lush green hills, villages along the coasts, and famous black sand clear water holiday beaches (Fergus, 1989). The island's land area is 39 ½ square miles. Three mountain ranges dominate the skyline, the northernmost Silver Hills, the Centre Hills, and the southernmost Soufrière Hills[3]. Plymouth was the principal city of the island. Plymouth hosted the island's center for sea transportation (an unsheltered harbor) and the island's center for air transportation was a small airfield on the east side of the island (see Figure 2).

Prior to the volcanic crisis, most of the island's population base resided on the southern two-thirds of the island. The 1991 population of Montserrat was 10,625 persons. Of that population, 2,766 or 26% of the total population resided in an area now known as the northern safe zone (Physical Planning Unit, 1999). The other 74% of the population lived in close proximity to the Soufrière Hills. The city of Plymouth[4] was the capitol city and administrative center for the island. Despite being only approximately three and one-half miles west of the Soufrière Hills volcano, most of the citizenry did not feel threatened as the volcano was considered to be 'extinct'.

In the late 1980s, Montserrat's economy was characterized as follows, "Montserrat is classified as a developing county, but it balances its recurrent budget and its people enjoy a creditable standard of material prosperity in spite of the insubstantial base of its externally-oriented economy" (Markham & Fergus, 1989). Economically, Montserrat had a light manufacturing sector, an agriculture sector (especially sea-island cotton), a tourism industry, offshore banking, an offshore medical school, and a regional

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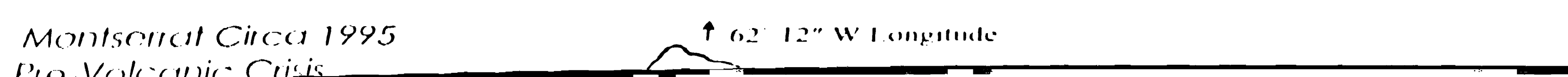
[2] This description is cited from a 1989 Montserrat Guide. One of the three 'extinct' volcanoes is no longer 'extinct'.

[3] The highest point of the island was in the Soufrière Hills at Chances Peak with an elevation of 3,002 feet. Currently, the volcanic eruptions have substantially changed the topography of the Soufrière Hills.

[4] The 1991 population of Plymouth was 1,083 people.


Montserrat Circa 1995
Pre-Volcanic Crisis
62° 12" W Longitude

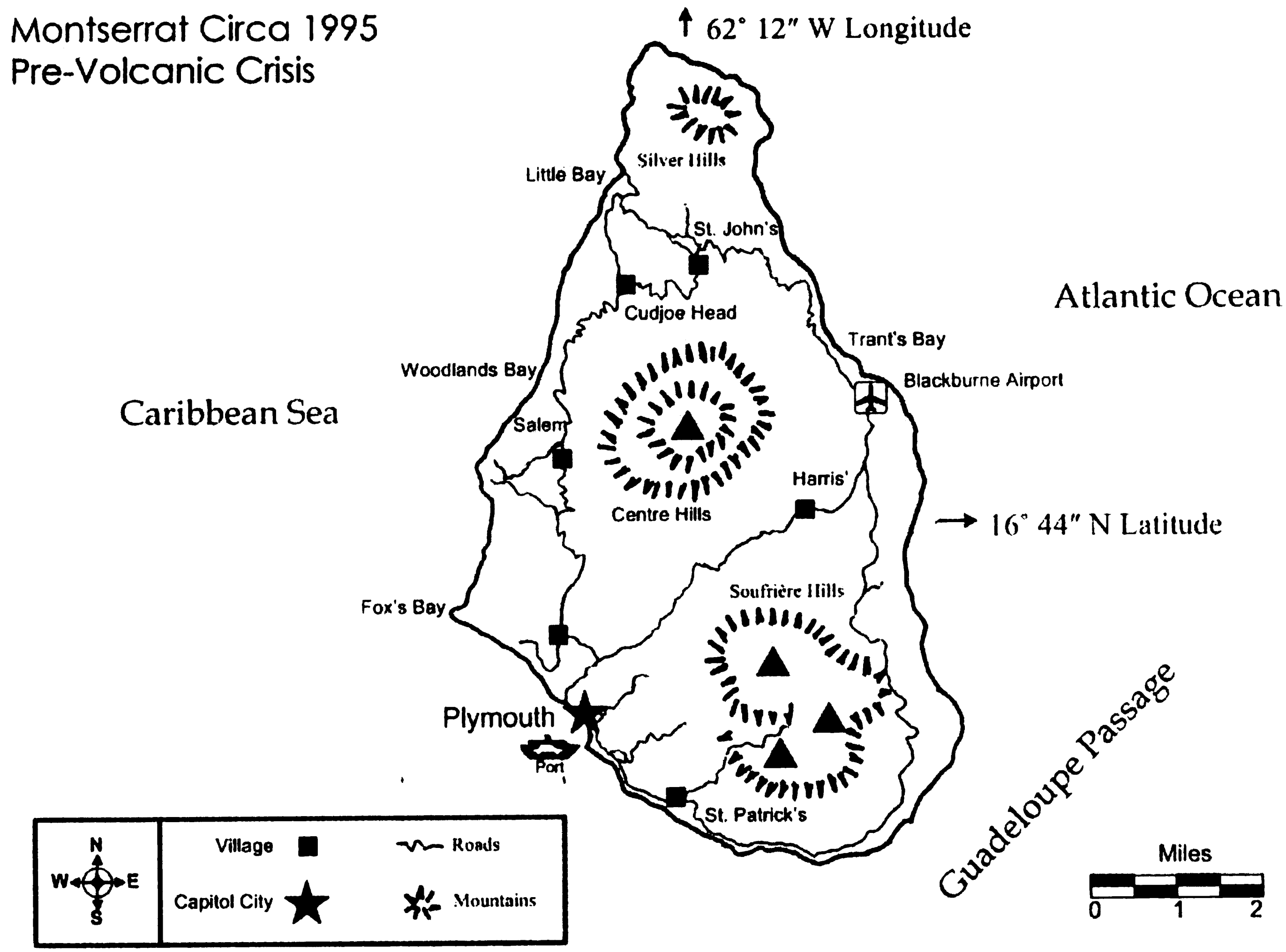


Figure 2. Generalized Map of Montserrat (Adapted from Berleant-Schiller, 1991)

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broadcasting / recording center. In the early 1980s, the economy for the island was called 'relatively buoyant' and the island felt little need for British budgetary aid (Fergus, 1989). However, by the late 1980s, the island had a trade deficit of about US$24 million. The trade deficit was balanced by remittances of èmigrès living abroad[5] and the incomes of foreign expatriates (Berleant-Schiller, 1991). The functioning of the island's economic system entirely disrupted during the volcanic crisis.

Socially, Montserrat's population is similar to other to that of the other Eastern Caribbean Islands. A dominant demographic influence of the old sugar and slave colonies is present. However, Montserrat remains unique as it was settled by English and Irish Catholics, who in the 1630s found refuge on the small island from Protestant prosecution. To this day Montserrat maintains an Irish Legacy, part superficial and part more permanent (Fergus, 1994). The *'Emerald Island of the Caribbean'* moniker as well as most local surnames[6] and geographic place names are Irish in origin. In the late 1990s, the island's population was composed of a majority of Afro-Caribbean persons, and a minority population of expatriates[7] (British, American, and Canadian) and British civil servants. During the volcanic crisis, the entire social structure was turned upside down as

[5] Montserrat has been called a 'prototypical emigration society' (Berleant-Schiller, 1991) meaning that during most of the Twentieth Century as the plantation system declined and population had to be balanced with resources many families encouraged the emigration of young people to ensure the survival of the society as a whole as well as the émigré. Many small-island states have well developed émigré communities where out-migration becomes a goal towards which young persons strive.

[6] As slaves had no surnames, when the British abolished slavery on Montserrat in 1838, the former slaves often adopted the only names they knew, that of their masters. Thus on Montserrat many Afro-Caribbean persons have Irish surnames (Fergus, 1994). Some commentators have claimed the 'Emerald Island' concept is more designed to attract tourists that actual demographic scholarship.

[7] During the 1960's Montserrat was promoted as in England and North America as an idyllic place to retire or build a second home. Part of the idyll was an English speaking Caribbean colony without an active independence movement (Berleant-Schiller, 1991). As Montserrat was deemed safe for outside investment by foreigners, the island became a destination for 'residential tourism'. Expatriates who have remained on Montserrat during the disaster have a genuine interest maintaining the island's quality of life.

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many of the island's residents, from all social groups, were evacuated under emergency conditions.

Politically, Montserrat is a British crown colony. The island has a locally elected government along with a British Governor who is the crown representative. For the most part, during the late Twentieth century the island had full self-government until a 1989 revision of the constitution in which more power was granted to the British Governor. In general, Montserratians have preferred to remain a British Overseas Territory rather than face the risks of an independent statehood founded on limited resources (Berleant-Schiller, 1991). Geopolitically, Montserrat finds itself in the unique position of being one of the few remaining remnants of the British Empire. Globally, there are only 16 non-self governing territories[8] in existence (Richardson, 2003). The volcanic crisis has reinforced the island's dependency on Britain.

This author would be remiss in not mentioning that immediately prior to the volcanic crisis, Montserrat was just beginning to fully recover from the natural disaster of Hurricane Hugo. On September 17, 1989, Hurricane Hugo hit Montserrat directly. As a result of the direct hurricane impact, 98 % of the houses (50% severely) were damaged, and 20% of the houses were destroyed completely. Nearly, a quarter of the population was left homeless. A British government disaster team estimated losses to be at £282,750,000 (Markham & Fergus, 1989). All sectors of Montserrat's infrastructure and economic base were severely damaged. Unfortunately, post-Hugo reconstruction continued right up to the time the volcanic crisis started. It was reported that builders were still painting the new library in Plymouth, the rebuilt government headquarters had

[8] In 2003, the 16 non-self-governing territories were Anguilla, American Samoa, American Virgin Islands, Bermuda, British Virgin Islands, the Cayman Islands, the Falkland Islands, Gibraltar, Guam, Montserrat, New Caledonia, Pitcairn, St. Helena, Tokelau, the Turks and Caicos, and Western Sahara.

yet to hold a legislative council meeting, and the improved hospital has yet to receive a patient (Pattullo, 2000).

2.4 The Soufrière Hills Volcano

This section addresses the origin of the natural disaster on Montserrat, the Soufrière Hills volcano. There is substantial scientific literature on the eruption of the Soufrière Hills (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004). Three main collections of scientific information have been published: Volume 25 of *Geophysical Research Letters* (Aspinall *et al.*, 1998); Memoir 21 of the *Geological Society of London* (Druitt & Kokelaar, 2002); and, Volume 44, Issue 8 of the *Journal of Petrology*, 2003. For the purposes of this study, that work will not be reviewed in detail, rather select sources will be drawn upon as necessary. Both a simplified overview of the primary geologic processes of the volcano and a brief explanation of key events in the eruptive sequence are provided here, as this information is relevant to understanding the context of the analysis provided by this study.

As Montserrat exists in a multiple hazard environment, the island has been impacted by disasters prior to the volcanic eruptions. The most recent of these disasters was the impact of hurricane Hugo in 1989. The volcanic disaster has two major differences from the other disasters. For example, with a hurricane, the disaster event is a singular event. Once the disaster occurs, the recovery then takes place in a sequential process. Also with other events, once the disaster strikes, recovery takes place at the location where the damage occurred. In the volcanic crisis, the disaster is ongoing where there are times of disaster, followed by times of calm, and then times of disaster (again).

Also, due to the nature of the volcanic hazard, once the disaster occurs it is often impossible to rebuild at sites which were damaged.

Geologically, the activity at the Soufrière Hills volcano has been characterized as fairly typical of that at many historically active volcanoes constructed of lava-dome complexes[9]. However, what sets the Soufrière Hills eruption apart is its continuous activity. In a 2003 summary of impressions from a meeting of Montserrat's Scientific Advisory Committee it was stated that, "We also believe that the odds are small that the current eruption will cease within the next six months; from worldwide experience, the activity is much more likely to continue for years, if not decades (Komorowski and Tilling, 2003)."

Geographically, the Soufrière Hills volcano is located at a subduction zone. At subduction zones, tectonic plates collide and one of the plates is pushed down into the interior of the earth and melts. Montserrat lies along the boundary of the Caribbean Plate and the South American Plate. This fact is important because it directly relates to the types of hazards presented by Montserrat's volcano. At subduction zones, the lava is relatively cool[10] and contains volcanic gas. These characteristics cause the lava to exhibit characteristics of stiffness and extremely slow movement. As this Andesite lava slowly moves toward the surface at the volcanic vent, it tends to pile up slowly around the vent forming a large pile of lava called a lava dome (Lea and Sparks, 2001).

Eruption events on Montserrat have been caused by specific events: vulcanian explosions or the collapse of the lava dome (Nakada, 2000). Vulcanian explosions are

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[9] Similar volcanoes to the Soufrière Hills are Unzen (Japan), Merapi (Java, Indonesia), and Mount Hood (U.S.A.) (Komorowski, 2003).

[10] The relative 'coolness' of the magma at the Soufrière Hills Volcano is 850 centigrade as compared to the magma at Hawaiian type volcanoes which have temperatures of 1200 centigrade (Lea & Sparks, 2001).

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small to moderate blasts that eject material to heights up to 20 kilometers on the order of minutes to seconds. These explosions are characterized by violent blasts, the ballistic ejection of rocks, atmospheric shock waves, and large ash plumes that can reach tens of kilometers in altitude (Morrissey & Mastin, 2000).

In addition to the eruptive events of vulcanian explosions, a collapse of the lava dome results in eruptive type events consisting of pyroclastic flows and surges. When the lava dome builds up the extent that it cannot support its own weight and gravitationally collapses, volcanic material flows outward from the collapsed dome in an explosive-like fashion. These explosions expel mixtures of hot lava blocks, ash, pumice, and volcanic gasses that descend the slopes of the volcano at high rates of speed. Such pyroclastic flows are amongst earth's most dangerous natural phenomenon[11]. On Montserrat, scientific teams placed instruments in the path of pyroclastic flows and the data recorded indicated that these flows reached speeds of 15 to 30 meters per second and with temperatures ranging from 99 to 250 centigrade (Nakada, 2000).

In considering the sequence of events leading up to the eruptions, it is now understood that precursors to the volcanic crisis were observed with the measurement of small earthquakes from 1992 to 1995. However, during the time periods of 1933-1937 and 1966-1967 thousands of small earthquakes were also measured, but none of those had led to large eruptions so such seismic activity did not necessarily indicate a pending eruption. The reactivation of the volcano in the mid-1990s took many people by surprise as no precursor activity was noted in the days immediately preceding the activity (McNutt *et al.*, 2000) .

[11] Pyroclastic flows have been responsible for some of the worst natural disasters in history. On the nearby island of Martinique, in May 1902, the city of St. Pierre was engulfed by a pyroclastic surge from the nearby Mt. Pelèe. The entire population of the city nearly 28,000 people was killed in minutes.

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Most accounts of the volcanic crisis indicate that it started in July 1995. On July 18, groundwater heated by magma flashed into a steam driven explosion, and this phreatic explosion sent an ash cloud over Plymouth. The situation was described as follows:

> "An unusual day in Montserrat, especially for those living in southern areas. On that afternoon, residents gradually became aware of an unusual roaring sound, quiet but persistent, coming from the mountains. At first it could have been taken for the sound of a distant aeroplane, except that it didn't go away. Residents of some areas reported falling ash, and there was an unusually strong smell of sulphur. People began to wonder if the unthinkable was about the happen – the volcano coming back to life" (Buffonge, 1996).

It was reported that the situation got progressively worse on August 21, 1995, when a larger explosion sent a cloud of black ash over Plymouth. With that event, most people evacuated the capital (Lea and Sparks, 2001). As of August 1995, it was clear that the volcanic crisis had the potential of becoming a serious disaster.

In November of 1995, lava reached the surface and a red-hot glowing Andestic lava dome was observable. In late-1996 and early-1997, the dome built up to the extent that the unstable pile of lava began to collapse on itself, bringing the first dome collapse in March of 1996. As the dome continued to rapidly build, dome collapses began to occur with greater frequency. In May 1996, a pyroclastic flow from a dome collapse reached the Caribbean Sea and began to build a delta of new land (Lea and Sparks, 2001). Then, the largest dome collapse recorded to date occurred on September 17-18, 1996. In a scientific report the event was described as follows:

> "The profound dome collapse led to conduit depressurization and then to an intensive, explosive, nearly vertical eruption column that lasted for nearly an hour. Conduit overpressures are estimated as 20 MPa. The eruption created an ash plume at least 11.3 kilometers high, leading to several encounters with civilian aircraft. A shower of hot ballistic rocks as large as 1 meter in diameter rained on the community of Long Ground. 2 kilometers east of the crater,

shattering roofs and igniting houses. Thankfully, the community had been evacuated several months earlier" (Montserrat Volcano Observatory Team, 1997).

Even after the dome collapsed multiple times in 1996, during the first one-half of 1997 it continued to replenish itself with new andesitic magma. In April 1997, the island was divided into seven volcanic risk zones (see Figure 3). On June 25, 1997, a lava dome with a volume of approximately 5 million cubic meters collapsed sending lava and pyroclastic flows over the northern flanks of the volcano at speeds of over one-hundred kilometers per hour. The flows and associated surge clouds covered about 4 square kilometers and damaged between 100 to 150 houses. This event also caused causalities as it as reported at the time there were eight people were confirmed dead, 11 people were missing, and five people who suffered serious burns (Montserrat Volcano Observatory Team, 1997a).

On July 31 and August 1, the capitol city of Plymouth succumbed to pyroclastic flows. Ever since the June eruptions, Plymouth had been under increased threat with pyroclastic flows following the path of Fort Ghaut[12], a ravine that runs through the city. The situation was described as follows:

> "Although some houses besides the ghaut in upper Plymouth and Gauges had been previously burnt, this was the first time so many buildings had been set ablaze. Residents of the safe areas flocked to vantage points in Salem and Friths, from which they could view the orange glow that marked the destruction of Plymouth (Buffonge, 1997)."

Then from August 3-12, 1997, a series of continuous large volcanic explosions ccurred. The lava dome growth from August and September 1997, from ended in the ollapse of about 9 million meters of lava in a pyroclastic flow that destroyed the island's

hhaut is a local term describing a deep ravine that runs down the side of mountain. During the eruptions, uts served as channels for pyroclastic flows.

Montserrat: April 15, 1997
During Volcanic Crisis

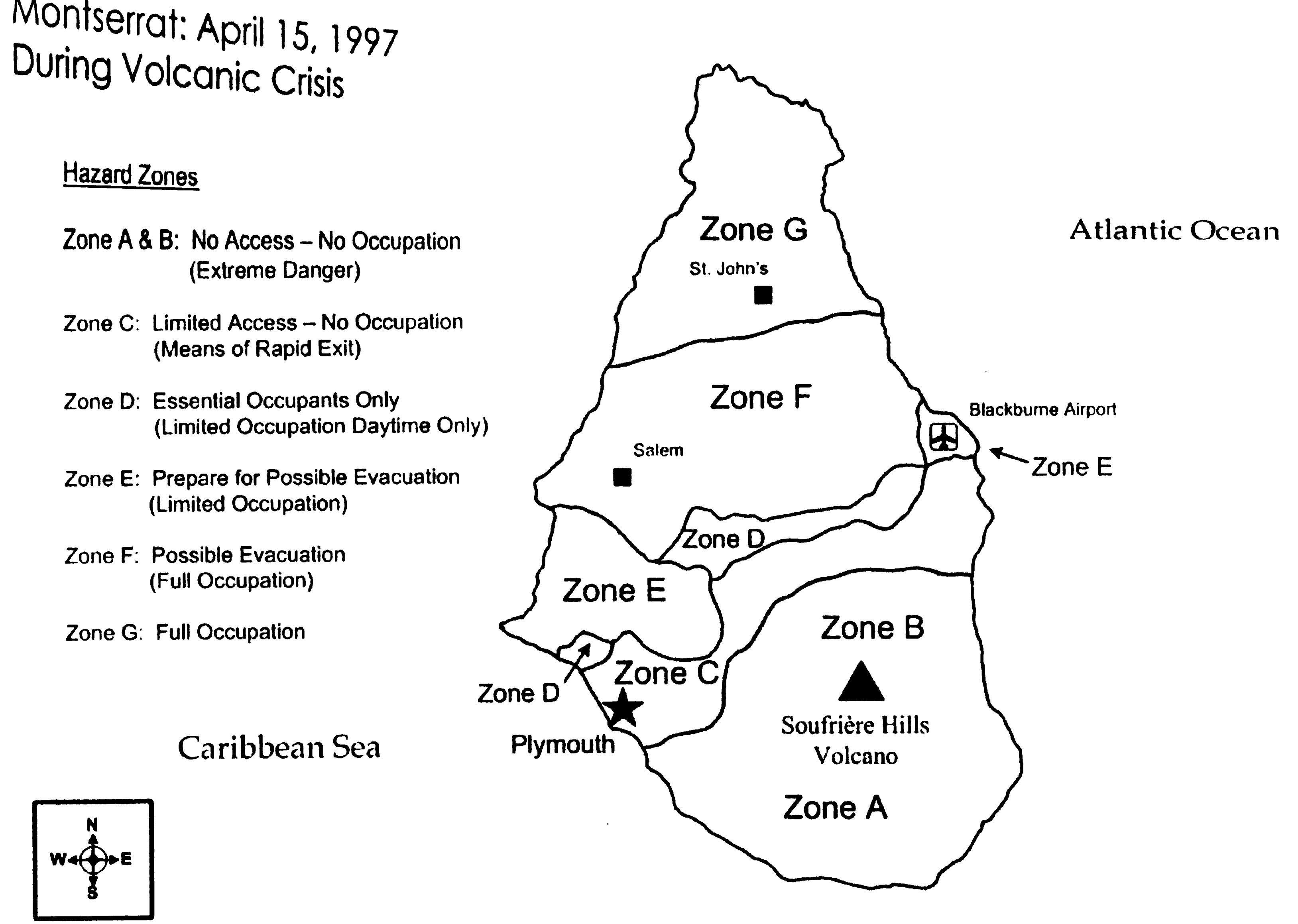

Figure 3. Seven Volcanic Risk Zones in 1997 (Adapted from Montserrat Volcano Observatory Maps)

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airport (Lea and Sparks, 2001). At this point, most of the island's critical infrastructure had been destroyed including the island's, seaport, airport, and capital city.

Following that large event, with little if any precursor activity, during late October and early September 1997, a series of vulcanian explosions occurred at approximately 10 hour intervals. In total, 76 large explosions occurred and ash clouds were sent up to 40,000 feet with pumice fragments falling all over the island (Montserrat Volcano Observatory Team, 2001).

The lava dome continued to grow to its largest volume to date (approximately 110 million cubic meters) and then largest eruptive event of the entire eruption occurred. This event occurred on Boxing Day[13] 1997. The large lava dome had been growing over an area of weaker rocks. When these weaker rocks failed a large volcanic landslide occurred undermining the dome and resulting in an unprecedented volcanic blast completely devastating a 10 square-kilometer square area of southwestern Montserrat. Entire villages were blown apart, and what was left was swept to the sea (Lea and Sparks, 2001). It is interesting to note that during the Boxing Day dome collapse a tsunami was generated as the blast and subsequent volcanic material reached the sea. Part of the small wave reached portions of Montserrat's shore where objects were displaced including a small boast and a stone table (Montserrat Volcano Observatory Team, 1998).

One of the most important measures of the size of volcanic eruption is the volume f erupted magma. During the last six months of 1997, the rate of the eruption increased about 7 cubic meters per second, an amount of material that is hard to imagine. To 'p the public understand the rates and volumes of the 1997 eruptions, scientists cribed the rate as the number of automobiles erupted every day. It was assumed that

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an auto has a volume of 7 cubic meters. Given that there are 86,400 seconds in a day, the volcano at the height of its 1997 activity was erupting an equivalent volume of 100,000 autos per day (Lea and Sparks, 2001).

From March 1998 to November 1999, there was a 20 month period with no lava extrusion into the dome (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004a). However, despite the situation of no new lava being extruded, eruptive type events still occurred since a large lava dome was already built up. Over time, that lava dome would weaken and weather eventually leading to another collapse. The situation was complicated by heavy rainfall and wind speeds of approximately 100 miles per hour related to passage of Hurricane Georges on September 1, 1998. The rainfall caused lahars, or volcanic mudflows and flash floods (Montserrat Emergency Department, 1998). Large amounts of loose unconsolidated volcanic material were transported from the upper flanks of the volcano to lower areas following ghauts and previous pyroclastic flow paths. Areas such as the city of Plymouth began to be slowly buried under volcanic debris. In one of the more significant events of that period. on July 20, 1999, a large dome collapsed occurred with pyroclastic flows in already devastated area and an ash cloud reaching 35,000 feet traveling as far the Island of Saba[14] (Montserrat Volcano Observatory Team, 2001).

By the year 2000, most of the major volcanic events had occurred and the oundaries of the exclusion zone and the safe zone had generally been established. In eneral the island was divided into three zones. The southern one-third of the island was exclusion zone and at the highest risk. This zone surrounding the volcano is off limits ll times. A central zone was established as a zone of medium risk and as volcanic

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e island of Saba is a part of the Netherlands Antilles approximately 100 miles northwest of Montserrat.

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conditions changed, it boundaries were redrawn into an area called the daytime entry zone on the central western coastal area of the island. The daytime entry zone has limited occupation. The northern one-third of the island is called the northern safe zone, and it is a zone of lesser risk. This zone has full occupation and all activities on the island take place in this area.

Given that the risk zones and ongoing crisis settlements patterns were generally established by 2000, volcanic events will not be described in the amount of detail as the events of 1995-2000. From 2000 to 2001, there was variable dome growth, and a notable dome collapse occurred in July 2001. In the period between July 2001 and July 2003, the longest time between major collapse events was observed. This long period of sustained dome growth at relatively low flux rates created the conditions necessary to achieve a very large dome size (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004). Again, in July 2003, a major dome collapse occurred. By July of 2003, the dome had reached its largest size since 1995. The volume of the dome was estimated to be 200,000,000 cubic meters the summit height was about 1100 meters above sea level. At least 60% of this dome collapsed during an 18-hour period over July 12-13, 2003. This was by far the largest collapse event of the eruption (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004). The pyroclastic flows generated from this large dome collapse impacted areas in the exclusion zone which were already off limits, but airborne ash from this dome collapse fell on western and northwestern Montserrat. The sh cloud was reported to have reached 40,000 feet and rock and ash in the form of 'wet ud' rained down on the entire island collapsing some roofs (Reuters Newswire, 2003). h reached as far as the U.S. Virgin Islands, as it was reported that on St. Croix, a man died when his car swerved off the road because of poor visibility due to the ash (Roach, 2003). Following the July 2003 event, the volcano was very quiet for nearly 8 months until a March 3, 2004 event involving collapse of part of the remains of the dome emplaced in 1997, together with explosions, destroyed the "domelet" from the previous July (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004a).

In 2004, in a period where little new magma has been extruded, the question has been asked, "Is the eruption over?" In order to attempt to provide an answer to that question, the Montserrat Volcano Observatory has developed a set a criteria based on measurements and observations. A scientific advisory report from a March 2004 stated.

> "Applying the criteria to observations from August 2003 to March 2004, it was concluded that the eruption could not be considered to be over. This does not mean that the dome will definitely start to grow again, only that the volcanic system is not inert, and still has the potential to erupt. We use the term "stalled". A stalled volcano may remain at a stop, or it may resume surface activity" (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004).

At the time of writing, the latest scientific assessment concerning the state of the volcano completed in September 2004. It was stated:

> "We consider that the volcano is still capable of producing explosions or extruding more lava. This does not mean that it definitely will do so. We estimate that the probability that it will NOT explode or extrude lava within the next year is about 40%. ... Thus the eruption cannot be considered over yet. This does NOT mean that the volcano will definitely start to erupt lava again in the next months to years. We consider that, although the volcano appears quiet outwardly, at depth it continues to show signs of being active and could re-start lava extrusion again in the next months"(Scientific Advisory Committee on Montserrat Volcanic Activity, 2004a).

Currently, there are two main causes for volcanic hazards for the foreseeable uture. If there is a situation with no sustained dome growth hazards faced are explosions ith ash and rock fallout, pyroclastic flows from explosive column collapse. In the ernative scenario of continued dome growth, the volcanic hazards faced are explosions with ash and rock fallout, pyroclastic flows from explosive column collapse, and pyroclastic flows from dome collapse (Scientific Advisory Committee on Montserrat Volcanic Activity, 2004b).

One definition of a disaster is "A process / event involving a combination of a potentially destructive agent(s) from the natural and / or technological environment and a population in a socially and technologically produced condition of environmental vulnerability (Oliver-Smith, 1996, pg. 305). Montserrat's volcanic crisis clearly exhibits many characteristics of a disaster, in the worst-case scenario. The potentially destructive agent arises from the natural environment, the Soufrière Hills volcano. Montserrat's human settlements were historically developed on the southern two-thirds of the island, in close proximity to the Soufrière Hills creating a socially produced condition of environmental vulnerability. Locating human settlements in close proximity to volcanoes is not an uncommon practice, as volcanic soils support some of the world's most important cash crops[15] (Ping, 2000). In the case of Montserrat, the delicate balance of the long quiet volcano with the preferred location for settlements in proximity to the volcano was violently interrupted with the recent volcanic events.

Going on 10 years after the initial events precipitating the volcanic crisis, the situation is still dynamic. These circumstances make the Montserrat disaster unique and present many uncertainties for the long-term redevelopment effort on the island.

2.5 The Disaster's Impact on Montserrat's Population

In addition to observing the sheer amount of physical destruction on the island, observations of Montserrat's population decline during the crisis also highlight the

[15] It is estimated that while volcanic ash soils cover slightly less than 1% of the earth's surface, their importance to civilization is great as volcanic soils support agricultural production for more than 10% if the total world population.

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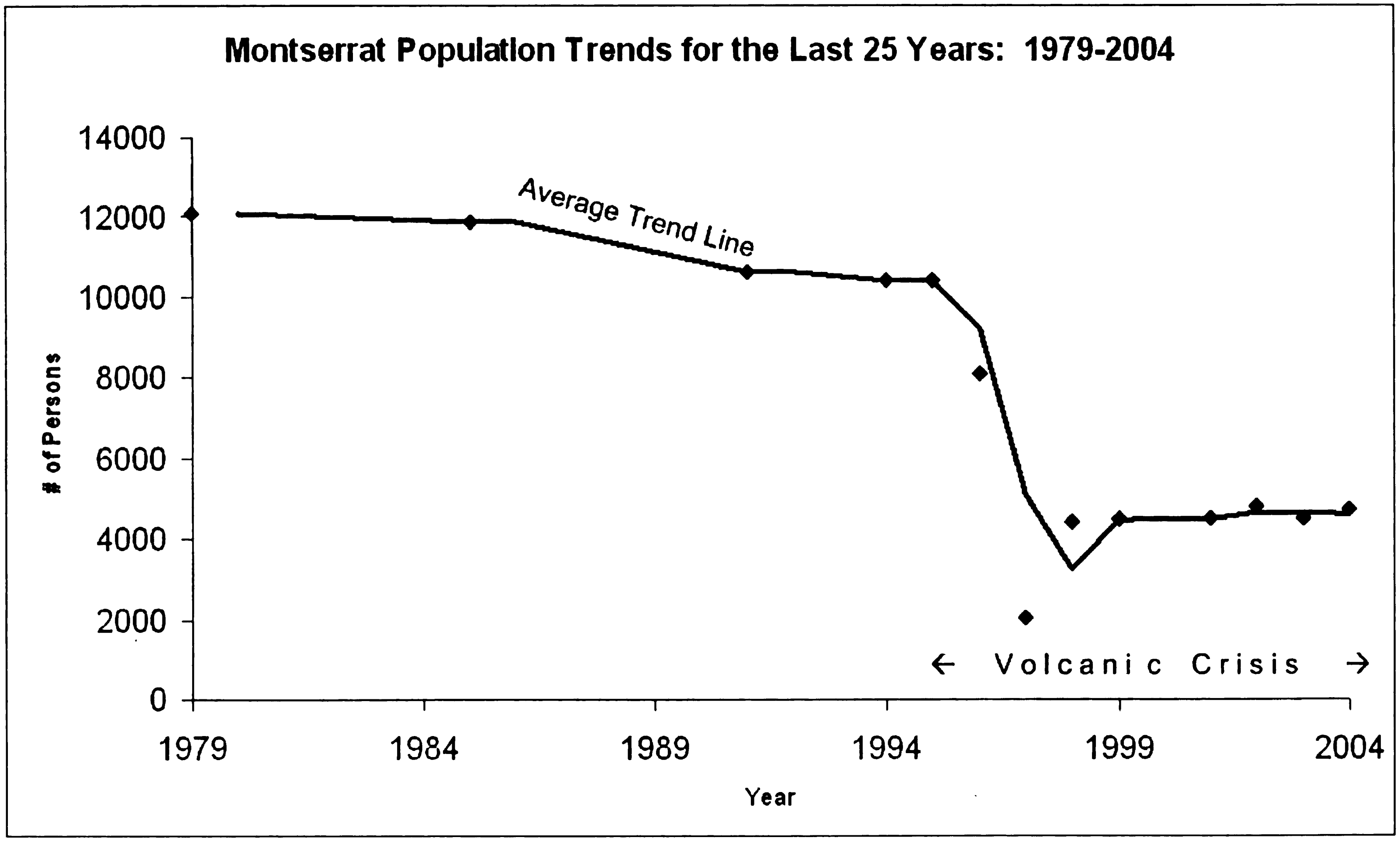
magnitude of the disaster. Since 1946, the population of Montserrat has been declining and it was estimated that the population would fall below 10,000 by the year 2000 (Development Unit, 1995). In the 1980s, the island's population was approximately 12,000 persons, and in the early 1990s, the population was approximately 10,000 persons.

Figure 4, Montserrat population trends for the last 25 years, illustrates the effect that the volcanic crisis had on the island's population. In 1995, at the start of the volcanic eruptions, the population was 10,400 persons (Development Unit, 1995). Once the crisis commenced, the population drastically declined as the southern two-thirds of the island was destroyed. Many persons left by their own means as the situation deteriorated from 1995 to 1997. In addition, a voluntary evacuation was initiated by the British Government at the height of the crisis. This author found many conflicting population figures for dates during the volcanic crisis. Such conflicting data is typical of a disaster situation with rapidly changing situations. For that reason, Table 1 provides the sources for the population data points, and a running average is line is plotted in Figure 4 to illustrate the general trend. For example in 1997, it was reported that 74% of the population had to be evacuated from their original residences and the population reached an all time low of 2,850 people (Development Unit, 2001). Another data source listed the November 30, 1997, population as 3,338 persons (Statistics Department, 1998). It is likely that with the chaos of the disaster during 1996-1997, the population figures drastically fluctuated on a month-to-month basis. By 2001, as the situation has somewhat stabilized, the population leveled off at approximately 4,400 to 4,700 persons. At the

Montserrat Population



Various Data Sources: See Table 1 for Complete Listing of Sources

Figure 4. Montserrat Population Trends for the Last 25 Years

YEAR
1979
1985
1991
1994
1995
1996
1997
1998
1999
2001
2002
2003
2004

Table 1

YEAR	POPULATION	SOURCE
1979	12,073	Patillo, P. (2000)
1985	11,852	Caribbean / Central American Action (1986)
1991	10,625	Physical Planning Unit (1999)
1994	10,400	Patillo, P. (2000)
1995	10,400	Development Unit (1995)
1996	8,069	Physical Planning Unit (1999)
1997	2.038	Development Unit (2001)
1998	4,400	Physical Planning Unit (1999)
1999	4,471	Development Unit (2001)
2001	4,470	Montserrat Volcano Observatory (2001)
2002	4,775	Montserrat Volcano Observatory (2002)
2003	4,483	Government of Montserrat (2005)
2004	4,690	Government of Montserrat (2005)

Table 1. Sources for Population Data Used in Figure 4

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time of writing, the population figure cited for the island will be 4,690 persons (Government of Montserrat, 2005).

Related to population, Montserrat had experienced casualties during the volcanic crisis. Due to the foresight of the Government of Montserrat and the British Government, combined with the advanced warnings from scientists at the Montserrat Volcano Observatory, casualties have been kept to a minimum. However, on June 25, 1997, the massive dome collapse and its associated pyroclastic flows inflicted the first and only direct volcano-related causalities to date. On that day, it was reported that nine people were initially killed and 17 were missing. As land rescue was out of the question, since the pyroclastic flows left superheated deposits that would not cool for weeks, helicopter-based search and rescue missions airlifted 30 persons to safety (Buffonge, 1997). In all, 19 persons were eventually confirmed dead (Pattullo, 2000).

It should be noted that all the casualties occurred in the exclusion zone, which was evacuated for over a week prior to the deaths. For reasons, varied from fatalism to distrust of authorities, to persons unable to comprehend or act on warnings some people did not heed ample warnings and remained in the small villages of Harris, Windy Hill, Stratham, Farrells, Bramble Villagem Tuitts, Bethel, Farms, Spanish Pointe, and Trants, as well as some of the surrounding agricultural lands. It has been reported that some of the farmers killed reoccupied off-limits areas to tend to their rich volcanic soil plots. They avoided official checkpoints, set up to prevent travel into hazardous areas, to tend to their farms. Such farmers have been described as, "Hard working folk who were reluctant to leave their crops and livestock to live in evacuation shelters in the safe zone, and depend on tinned food and government handouts" (Buffonge, 1997, pg. 37).

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While not meant to diminish these tragic events, the extent by which casualties were minimized on Montserrat is indicative of both advances in late-Twentieth century science and the foresight of emergency management authorities on the island. For comparison, one could look to the 1902 Mt. Pelèe eruptions, on the nearby island of Martinique, where the city of St. Pierre was engulfed by pyroclastic surges. In that disaster 28,000 people were killed. Volcanic hazards such as those faced on Montserrat are one of nature's most dangerous phenomena. Fortunately, urbanized areas at highest risk from the Montserrat volcano were evacuated prior to their destruction.

2.6 Uncertainty Created by the Volcanic Disaster

This author would be remiss in not acknowledging that beyond the sheer level of physical destruction caused during the volcanic eruptions, social and economic dislocations caused during the crisis bring with them a set of problems equivalent in complexity and importance to the physical aspects of the disaster. While this portion of the chapter does not represent a full survey of those issues, economic, social, political, and physical planning case examples are presented to illustrate how the volcanic disaster has created uncertainty at a variety of levels for Montserrat's recovery.

2.6.1 Post-Disaster Economic Uncertainty on Montserrat

In a paper presented seven years after the volcanic crisis started, an apt summary was provided summarizing the social and economic transformations that have taken place with the disaster (Greenaway, 2002). As cited directly from Greenaway, a comparison between pre- and post-volcano economic conditions was made.

Prior to the 1995 start of the volcanic crisis, Montserrat was characterized as follows:

- A positive economic growth of 5.26% in 1994 following the Post-Hugo rehabilitation
- Per Capita GDP of EC[16]$14,165 (US$5,200) - GDP EC$147.32m with a population of 10,400
- A vibrant and growing tourist sector contributing over 30% of GDP
- Good economic infrastructure with plans for further expansion in the air transport sector
- Balanced recurrent budget with small surpluses
- Good educational infrastructure with plans 99% access to education
- Excellent modern health facilities
- A fully functioning off shore medical school

In fall 2002, the same indicators were described as:

- Erratic economic growth
- Per Capita GDP of EC$15,383 (US$5,661) - GDP EC$75.96M with a population of 4,938
- A struggling tourism sector contributing approximately 10% to GDP
- Poor economic infrastructure with severe limitations in air and sea transport
- Budget deficits financed by budgetary aid
- Reduced educational facilities with limitations on access to tertiary education
- Minimum standard health facilities
- Social welfare programme
- No major private sector investment

[16] The currency used on Montserrat is Eastern Caribbean Dollar of EC$. The currency is set as fixed rate of EC$2.70 = US$1

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Clearly, the volcanic crisis had entirely disrupted the functioning of the island's economy. The nature of the volcanic eruptions, with the lack of a definite end-point, negatively impacts development prospects for the island. The issue of economic viability is important to Montserrat. A figure of £200 million has been quoted in official circles as the level of aid allocated to Montserrat up to the year 2000. Greenaway has suggested when one calculates that amount of aid in comparison to a population figure of 4,500 persons and an equivalent of £44,000 per person is being spent by the British Government to support life on Montserrat. That amount of spending per person raises the question of whether it is worth spending those sums of money on a country that may of may not be financially viable (Greenaway, 2002).

2.6.2 Post-Disaster Social Uncertainty on Montserrat

As the disaster has forced a massive off-migration, the social fabric of the island has been torn in ways that may be impossible to repair. This author suggests that just as Montserrat needs to undergo physical reconstruction and island must also undergo a social reconstruction. While such social forces add a layer of complexity to the post disaster redevelopment, one way to consider the situation may be by looking how larger social forces impact the ongoing-crisis.

Montserrat's disaster recovery is a case where larger social forces are interacting with, and influencing, the recovery process. One aspect of globalization, deterritorial-ization, is a useful concept to apply in order to understand some of the social dynamics influencing reconstruction on the island. The development of post-disaster new towns on the island and the social dynamics of Montserrat's post-disaster communities are ex-plicitly linked. No matter how much effort goes into the physical planning of postdis

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disaster new towns, social circumstances driven by external forces may create problems that make living in the reconstructed areas problematic.

The phenomenon of globalization is not new to the eastern Caribbean. Life on the islands became linked to the European-style state system in the mid-16th century, when European explorers first traveled to the Caribbean and Latin America. Since 1500, the forces of capital and coercion marked the arrival of a framework for connecting and integrating geographies via classes, the state, and markets (Watson, 1993). Presently, a phenomenon called globalization is effecting both the internal and external decisions that define the social structure of nations. While definitions of globalization vary, the term is used to signify the fact that something profound is happening and that a new world economic, political, and cultural order is emerging. This phenomenon can be characterized by a series of paradigmatic shifts in societal organization. They include intensive high technology production, the internationalization of economic diplomacy, innovation mediated production driven by incessant technological change, global production shifts, and ecological crisis (Axtmann, 1998). Existing conceptual frameworks for considering the interactions of nations cannot adequately account for these factors that affect individuals, groups, classes, nations, and geography as a whole. Issues of globalization in the Caribbean center on pivotal questions of nation, nation-state, sovereignty, hegemony, theoretical construction, and the capacity of the nation-state to manage domestic and global change (Watson, 1993).

One aspect of globalization, deterritorialization, is especially relevant to the Montserrat disaster. Deterritorialization is a recent approach to understanding the chaotic cultural processes in today's world (Appadurai, 1996). Before the volcanic crisis, Mont

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Montserratian society faced both tensions and fears related to cultural absorption by polities of a larger scale. As the volcanic crisis unfolded during the late 1990s, the off-island migrations caused by the disaster along with the infusions of foreign assistance for the relief efforts created fears among some Montserratians of the local culture being absorbed by Western influences. Part of the origin of these fears may be based on the fact that returning disaster refugees bring back with them ways of the world that are foreign to Montserrat.

In situations of deterritorialization, laboring populations are brought into the lower-class sectors of relatively wealthy societies, while sometimes creating exaggerated and intensified senses of criticism or attachment to politics in the home state. Deterritorialization affects the loyalties of groups (especially in the context of a complex diaspora), their transnational manipulations of currencies and other forms of wealth and investment, and strategies of the state. This loosening of hold between people, wealth, and territories fundamentally alters the basis of cultural reproduction (Appadurai, 1996). As the post-disaster reconstruction based on land-use and economic development plans rebuilds the necessary physical appurtenances for society to function, one could ask the question, "What plans or programs are being implemented to rebuild the damaged social fabric?" Currently on the island, the culture of coping with crisis has taken hold, while those who have evacuated, and are now returning, are bringing back with them a new cultural mixture of values and attitudes that mayor may not be compatible with the value systems existing on Montserrat.

As Montserrat recovers, one of the critical factors influencing the success of the newly constructed human settlements will be how Montserratians cope with the chaotic patte

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patterns of population movement both between the island and points abroad and between points on the island itself. The writer suggests that a double-deterritorialization has taken place on Montserrat.

According to 1999 data, about 6,500 people, or 51 % of the island's pre-disaster population was living elsewhere. In 1998, the Government of Montserrat Statistical Department estimated[17] that approximately 47% of the people who evacuated went to the United Kingdom, 39% went to Antigua, 13% went to other Caribbean countries, and about 1 % went to the United States. It is comparatively simple to travel from Montserrat to England (taking about one-half of a day) or to evacuate the entire island by sea (taking a few days), as compared with coping with the social impacts of these off-island migrations (which takes years). In theory, those families who left Montserrat for Britain can return to their homeland, but if they resided in one of the devastated towns on the southern portion of the island they will find their home community unrecognizable. Cities on the southern portion of the island have been completely devastated and they are now being buried by the combination of material deposited from the pyroclastic flows and other loose material eroding from the flanks of the volcano. Many of the geographic locations of these cities are unrecognizable, as the volcanic activity has completely changed the physical landscape of the southern portion of the island. People returning will need to both adapt to the loss of their community and integrate into the new cities being created in the northern safe zone. Notwithstanding the land and resource limitation questions, questions also exist on how these people will integrate back into Montserratian culture. These deterritorialized populations will have already negotiated new commodity

[17] Estimates were provided to the author from communication with the Government of Montserrat Statistics Department.

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patterns and they will have recalibrated their existing patterns of knowledge and practice to living abroad. Specifically, young persons evacuated from Montserrat during 1997, and subsequently living in the environs of British cities for the past few years, will adapt to the ways of European metropolitan culture. If these young people decide to return, it is an open question concerning what cultural patterns they will bring back with them, and whether these cultural patterns will smoothly fit into the existing Montserratian culture.

In addition to the issues of deterritorialization related to evacuation off the island, a different type of on-island deterritorialization is simultaneously taking place. This deterritorialization consists of people being evacuated from the southern portion of the island to the northern portion of the island. During height of the crisis, while a majority of people left the island more than 3,000 others made the choice to stay on Montserrat, relocate temporarily, and then permanently to new communities in the northern safe zone. Just as those who left the island had to negotiate a new spatial setting, new neighbors, and new communities, people who remained faced also faced the deterritorialization of being completely uprooted and moved to the northern portion of the island. While this deterritorialization is not as dramatic as a deterritorialization from the West Indies to Europe, there are similar impacts of having to negotiate new territorial boundaries and identities.

Clearly different social groups on the island will be developing different needs, due to their specific post-disaster coping activities. The associated break-up of families and communities after the disaster has meant that individuals are now much more dependent on the state than in previous times. One of the goals of the planning document, *The Sustainable Development Plan: Montserrat Social and Economic Recovery*

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Programme - A Path to Sustainable Development 1998 *to 2002,* is to review the whole structure of (social) welfare so that it can be more efficiently coordinated, better targeted, and delivered more economically with the ultimate goal of reducing dependency in the long term (Government of Montserrat & Her Majesty's Government - United Kingdom, 1997). While social factors such as deterritorialization may seem complex to comprehend, considering such factors can help those people concerned with Montserrat's reconstruction move closer to constructively addressing the social uncertainties created by the disaster.

2.6.3 Post-Disaster Political Uncertainty on Montserrat

Any complex disaster recovery situation clearly has political implications and Montserrat is no exception. In the study of industrial disasters, questions have been raised concerning the assumptions about a return to 'normal' that underlie cyclical equilibrium models of disaster (Couch, 1996). It has been suggested that some disasters are essentially open-ended processes that may persist indefinitely. At least for the present time, the case of Montserrat's volcanic crisis appears to look like that. Given the changing state of the volcano, much uncertainty constantly overshadows policy decisions. Some commentators have criticized the widespread assumption amongst hazards researchers that public leaders want scientists to help them reach good decisions by eliminating uncertainty (Mitchell, 1999). It is been suggested that manipulation of uncertainty is a core political device that few leaders willingly surrender (Waterstone, 1993).

During the height of the volcanic crisis, rumors had circulated that a total evacuation of Montserrat was being planned. While contingency plans were in place to evacu

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evacuate the entire island under an extreme emergency, officials did not see the need to activate such plans (Buffonge, 1997). However, given the mere existence of such plans, persons taking a cynical perspective claimed that the British Government had a vested interest in a total evacuation of the island, as exercising that option would cost less than continually supporting a grant and aid based society. As scientific predictions concerning the volcano carried with them a degree of uncertainty, claims have been made that such uncertainty was being manipulated.

One example of a political controversy known as the 'golden elephants row' is described here as it is illustrative of the realities that can affect, for better or worse, progress towards disaster recovery on Montserrat.

In 1997, as the volcanic crisis was at its peak and Plymouth was being incinerated by pyroclastic flows, a voluntary evacuation scheme was put in place by the British government. Under the scheme, those who persons who wished to live on other Caribbean islands would have their transit paid and be provided up to £2400 (~US$3870) per person. People who chose to evacuate and resettle to England would have their fares paid, be given work permits, and have access to welfare for two years. For people who chose not to evacuate, the British Government promised £40.5 million for development aid in the future. However, the evacuation scheme was communicated to the islanders in a blunt manner, creating alarm and mistrust. Some islanders interpreted the actions as Britain trying to force them to leave the island by a sinister mix of bribes and delay in the provision of new housing (Anonymous [The Economist], 1997).

The locally elected government expressed public displeasure at the amount of aid the British Government was providing for relocating individuals and lobbied for a

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increased aid. The Montserratian Government presented a list of needs to British Government's Department for International Development (DFID) including more houses, a new hospital, a new airport, helicopter service, roads, a transport network in the north, and restitution fund for uninsured assets, and support for financial services (Pattullo, 2000).

Clare Short, the Secretary of State for International Development, reminded the Government of Montserrat of the need for fiscal restraint despite the trying times on the island. On August 24, 1997, in an interview with Miss Short that was published in the *London Observer* newspaper titled "Short's Golden Elephant Gaffe over Volcano Isle" she accused the Government of Montserrat of being greedy. She stated:

> "(The Government of Montserrat was) talking mad money, they say 10,000, double, treble, and then think of another number. It will be golden elephants next. They have got to stop this game. It is bad governance. It's hysterical scaremongering, which is whipping people up"(Wintour & Hillmore, 1997).

Later Miss Short apologized by saying, "I was foolish enough to use that startling phrase that I now regret"(Black, 1997). The *London Economist* stated, "For sheer tactlessness towards a stricken people facing the loss of their homes and livelihood, this statement must go down as one of the most brazen in the annals of diplomacy" (Anonymous [The Economist], 1997). However, they go on note that Miss Short was also faced with the difficult task reconciling the neglect of the previous administration's underfunding of the colonies needs and squaring her department's limited budgetary aid with the expensive new Montserrat commitment. The *Economist* editorial goes on to summarize that political state of affairs in August 1997 as:

> "Quite how this crisis will develop is as unclear as the size of the Soufrière volcano's next eruption. One certainty is that it will end up costing the British taxpayer a great deal more than the £50 million which Ms. Short has proclaimed

> is all the government can afford. Frank Savage, the island's British governor, says Britain will neither order Montserratians off the island nor force them to stay. But at present the islanders are faced with an impossible choice: a tiny sum of money to leave everything behind, or else stay without adequate shelter. Mr. Savage unwittingly sums up neatly what most locals believe is wrong with Britain's policy. The volcano is dictating the pace"(Anonymous [The Economist], 1997).

Since those events, both the British DFID and the Government of Montserrat have worked to mend relationships and both governments are now cooperating to reconstruct the island in the northern safe zone. The 'golden elephant's row' was one of the more widely publicized controversies and all sides learned from the unfortunate affair.

This author has noted that as the disaster continues, residents on the island continue to have varied reasons for discontentment that may find political or legal outlets. For, example a developing controversy surrounds the decisions concerning exactly where the lines and are drawn dividing the exclusion zone from the safe zone (Davison, 2003). Some property owners have expressed discontentment as their property that was once in once declared to be safe is now declared to be in an exclusion zone. During October 2002, decisions were made dividing a village into safe and unsafe zones. The decision was very unpopular among some expatriates whose villas fell on the wrong side of the line. As a result, scientists have worried that they could be vulnerable to litigation over advice they provide to the Montserrat Government (Stone, 2003) .

Social discontentment can lead to a potentially volatile political relationship between the colonial power and it subjects. Any policy decisions made need to take into account potential political implications that can lead to distrust which acts to impede the recovery process itself.

2.6.4 Post- Disaster Physical Planning Uncertainty on Montserrat

Once the disaster situation somewhat stabilized, the Government of Montserrat was able to engage in physical planning efforts to reduce the uncertainty related to how the island would redevelop. With the existing conditions on Montserrat, physical planning has necessarily been reactive and decisions have been made in response to urgent needs in a crisis situation (Physical Planning Unit, 1999). As the crisis was going into its third and fourth year, it became apparent that land use planning needed to shift from a reactive to a proactive basis. In 1998 and 1999, the Montserrat's Physical Planning Unit created a *Physical Development Plan for North Montserrat, 1999-2008.* The purpose of the document was to facilitate planning on a proactive basis. Future land development plans for Montserrat were based on the assumption that all future development needs will be met in the island's northern safe zone which is an approximately 15 square mile area.

A target approach to development planning on the island has been adopted based on attracting people back to the island and encouraging population growth. An overall target of 10,000 persons equates to the on-island population prior to the onset of volcanic activity and is considered realistic in terms of the carrying capacity of the northern part of the island (Physical Planning Unit, 1999).

From the perspective of built environment, the island's destruction was nearly complete. Every aspect of life needed to be recreated in the northern safe zone. For example, in Plymouth facilities lost included entertainment services; bakeries; bars; business and professional buildings; clothing shops; hotels; personal services facilities; restaurants; retail services centres; wholesale outlets; distributive trade centres;

educational and community facilities; health and welfare facilities; industrial facilities; public and protective services centres; utility infrastructure; warehousing facilities; and sporting facilities (Physical Planning Unit, 1999). In addition to Plymouth, the villages of Bethel, Bramble, Farms, Gingoes, Spanish Pointe, St. Patricks, and Trials were totally destroyed. The island's airport, many houses of worship, the American University of the Caribbean's offshore medical school campus, and island's main radio towers and communication masts were also destroyed. Besides the infrastructure elements lost, a total of 3,213 households lost their homes. In total, 7,243 persons were displaced from the southern portion of the island (Physical Planning Unit, 1999). In summary, the entire island needed to be re-planned from scratch.

During the crisis, the island was divided into multiple risk zones which shifted based on the degree on volcanic risk. Under such circumstances it was difficult to engage in any proactive physical planning activities. At the time of writing, the island is divided into three zones with the boundaries of the northern safe and exclusion zone well established (see Figure 5). The exclusion zone is entirely off limits except for the purposes of national security and scientific activities. The exclusion zone is not suitable for inhabitation. A small zone on the central western coastal highlands has been declared as a daytime entry zone. In this zone, if the volcanic risk is minimal, the zone is opened during daytime hours for persons to gain access their property. In this zone there are many observable effects of the volcanic eruptions. The northern safe zone is open to full occupation, and all redevelopment activities take place in this zone. The zone is mixture of older underdeveloped villages and new towns.

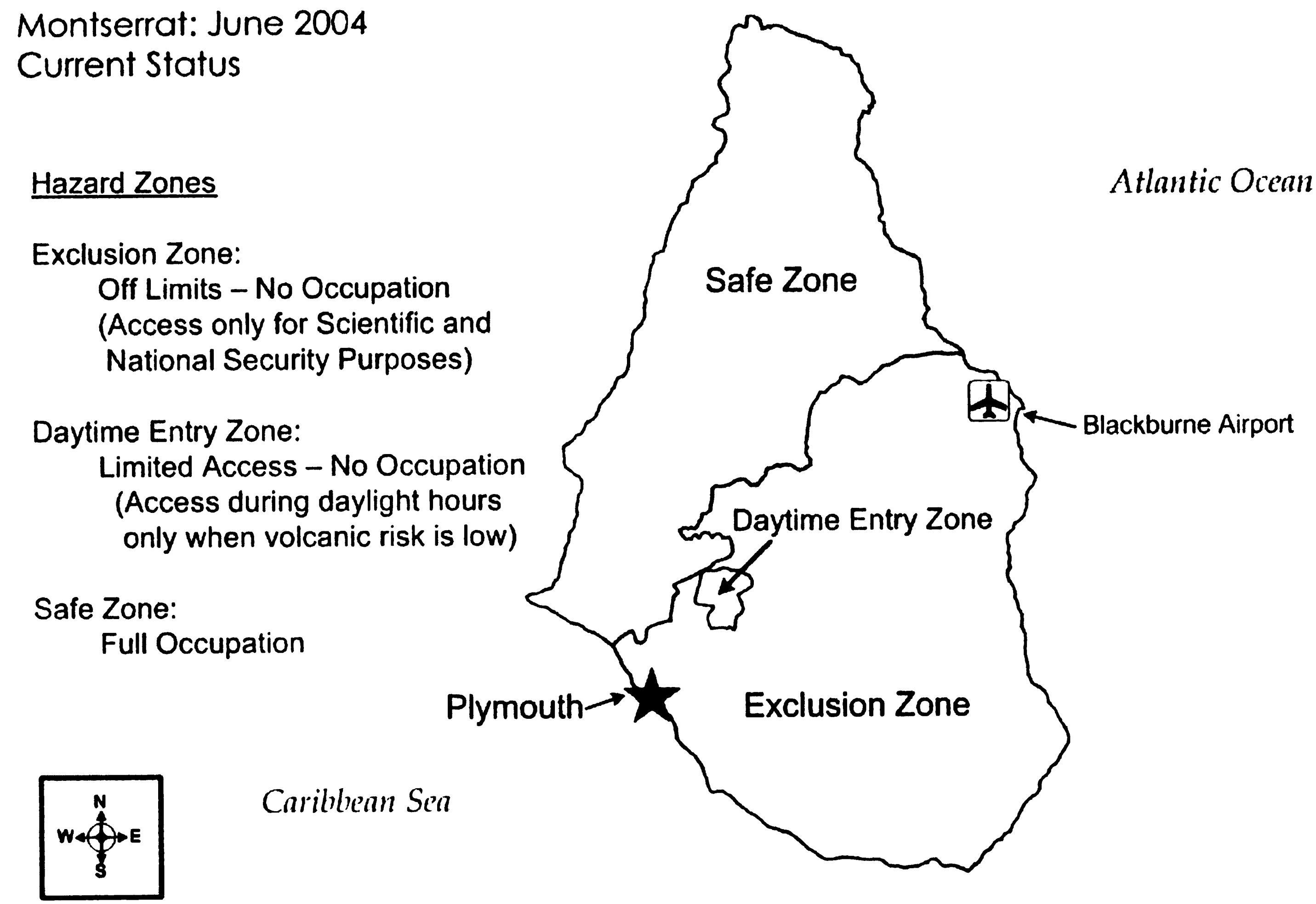

Figure 5. Current Montserrat Risk Zones
(Adapted from Montserrat Government Information Unit Map)

The physical development plan proposed to develop new activity centers at the following locations: Little Bay, Geralds, Lookout; Cudjoehead / Brades / Manjack, St. Peters, St. Johns, and Salem. At the time of writing new developments are taking place simultaneously in all of those urban centers.

Physical planning on Montserrat has faces challenges. Older villages in the north, such as St. Johns, are relatively underdeveloped. These older villages share the same problems as older town centers on many Caribbean islands. These towns are one to two centuries old, in a state of decay, and have an overloaded infrastructure. Traffic congestion, parking problems, and pedestrian-vehicular conflicts can also be severe on narrow, winding, very steep streets (Hudson, 1989). Such difficulties make large-scale urban planning projects difficult in existing villages. As a result is island is de-centered, with a series of linear small villages strewn wherever there is suitable land (and sometimes where there is not suitable land)(Dittmer, 2004). In some of the new Montserrat new towns, the urban pattern has been viewed as not consistent with the typical Eastern Caribbean urban patterns. One observer commented on the urban pattern at the new towns at Davy Hill and Lookout as follows, "These areas resemble Montserratian Levittowns with identical homes placed in geometric patterns on the steep hillside. The developments ignore West Indian lifestyles by eliminating the space and soil for house yard gardens that were so pivotal to traditional life before the volcano erupted (Pulsipher, 2001)"

Despite planning difficulties in post-disaster Montserrat, much credit needs to given to planners on Montserrat for moving forward to quickly re-plan an entire society under adverse circumstances. One could look toward more developed countries and find similar problems of sprawl, unplanned developments, and questionable design in much more resource rich environments where there is not an ongoing crisis. As new towns are being constructed on Montserrat, the main physical planning uncertainties will come not from the planning process itself, but from other economic, social, and political circumstances which may interfere with plan implementation.

2.7 A Permanent State of Crisis of Montserrat

To conclude the chapter describing the case of Montserrat's volcanic crisis, I will highlight one February 2005 episode that illustrates how volcanic crisis may be considered as permanent situation, at least from the perspective of the U.S. Department of Homeland Security.

On February 24, 2005, this author was contacted by radio station WBUR[18] for an interview on the Morning Edition news program regarding Montserrat refugees being sent back to Montserrat. In 1997, up to 300 Montserratians were granted Temporary Protective Status (TPS) to enter the United States. TPS status is granted to permit refugees to enter the United States on a temporary basis to flee dangerous situations, such as natural disasters or political instability. Since 1997, Montserratians' TPS status had been renewed seven times. The Department of Homeland Security (which now manages immigration issues) has revoked TPS status for those persons who fled the Montserrat volcano. On Sunday, February 27, 2005, TPS status expired for Montserratians residing in the United States. Homeland Security Department officials said, "The volcanic eruptions can no longer be considered temporary (on Montserrat) and TPS status is not meant to cure or resolve situations are indefinite with no realistic end in sight" (Desai, 2005). The refugees must either now leave the United States and return to Montserrat or

[18] WBUR is a Boston National Public Radio affiliate

immigrate to Great Britain. Persons affected are claiming that after living in the United States for seven years, they still have nothing to return to on Montserrat and it is not feasible for them to immigrate to England. In the Boston area, approximately 100 refugees are being affected and their future is uncertain at the time of writing.

This situation is relevant to this study, as it illustrates how for immigration purposes the situation on volcanic crisis on Montserrat is no longer considered to be temporary. As the crisis on Montserrat becomes to be considered as permanent, is an open question of how redevelopment of the island will proceed under a permanent crisis situation?

CHAPTER THREE

LITERATURE REVIEW: HAZARDS, RISK, AND DISASTER

3.1 Introduction to Literature Review

This literature review concerns the overlapping topics of hazard, risk, and disaster, as they are key concepts in this study. The field of natural hazard studies and disasters has its roots in human ecology, but it has diversified to include fields as geography, sociology, anthropology and beyond. Studies of hazards and disasters are often segmented into applied academic disciplines. Similarly, while general literature exists on the concept of risk, the field of study has also been segmented into the applied areas such as risk perception, risk communication, and risk assessment. Like the physical properties of strength and friction, risk fully evolves when mobilized by forces, such as in this case the destructive powers of hazards. Mostly, risk remains an abstract concept, and the public are congenitally unable to view the probabilities rationally (Alexander, 2000).

Clearly, the complexities of hazards, risk, and disaster lend themselves to an interdisciplinary approach. As this literature review illustrates, there are many ways in which these topic areas overlap. However, each of these areas of study also has its own distinct roots and specific disciplines which have driven key advances in thought.

A useful table illustrating the relationship between hazard and risk was developed by Cutter (Cutter, 2001). Table 2 represents a comparison of common elements of both risk assessment and hazards analysis as it illustrates how many of the same questions are addressed from both perspectives, but the methodologies used to respond to the queries are radically different (Cutter, 2001). She suggests that the major obstacles to the integration of risk assessment and hazards assessment paradigms are the methodological

Elements	Risk Assessment	Hazard Assessment
Hazard Identification	Does the agent / Toxin cause the adverse effect? Chemical Y has a 1 in q million chance of causing cancer in humans.	What is the threat? What is the occurrence of the hazard? Mapping of specific hazards and/or zones.
Dose-Response Assessment	What is the relationship between dose and incidence in humans? Exposure to X parts per million of chemical Y for a period of 2 days causes liver damage.	What are the magnitude, frequency, and duration of the event? What are the potential human consequences of the event?
Exposure Assessment	What exposure are currently experienced or anticipated under different conditions? How much of the toxin will reach a targeted population of how many people will receive some exposure?	What is the pattern of human occupance in hazard zones? What is the vulnerability of people and places to hazards?
Risk Characterization	What is the estimated incidence of the adverse effect in a given population? What is the likelihood that an agent of concern will be realized in exposed people?	What accounts for different adjustments and adaptations to hazards? How do societies prepare for, mitigate, and respond to risks and hazards?

Table 2. Risk Assessment and Hazard Assessment Paradigms
(Adapted from Cutter, 2001)

divides and the exclusive use of a reductionist analytical framework found in risk analysis. In risk analysis, the importance of the quantitative methods and models often excludes people as dynamic factors. On the other hand, it is also noted that the hazards paradigm must move beyond a simple descriptive methodology (quantitative and qualitative) to a more integrated analytical framework that permits the assessment of larger and more complex databases and more robust empirical field studies.

This study will incorporate elements of the hazard and risk assessment paradigms. Therefore, relevant literature in both the hazard and risk field will be highlighted. This literature review starts with definitions and then discusses aspects of disaster and risk research.

3.2 Key Definitions: Hazard, Risk and Disaster

When considering hazard, risk, and disaster, I will start with a set of definitions common amongst practitioners [19]. From a practitioner viewpoint, a hazard is defined as a "Source of danger that may or may not lead to an emergency or disaster, and it is named after the disaster / emergency that could be so precipitated." Risk is defined as "Susceptibility to death, injury, damage, disruption, stoppage, and so forth." A disaster is defined as an "Event that demands substantial crisis response requiring the use of governmental powers and resources beyond the scope of one line agency or service"(Haddow & Bullock, 2003).

Expanding those definitions from a domestic to international perspective, UNCHS HABITAT[20] has also defined hazard, vulnerability, and risk in the following ways. A hazard is "The probability that in a given period in a given area, an extreme potentially

[19] Common definitions of hazard, risk, and disaster were established by the National Governors Association in 1982.
[20] United Nations Commission for Human Settlements, Settlement Planning for Disaster, Nairobi, 1981.

damaging natural phenomenon occurs that induces air, earth or water movements, which affect a given zone. The magnitude of the phenomenon, the probability of its occurrence and the extent of its impact can vary and, in some cases, be determined." Related to hazard, vulnerability is defined as "vulnerability - of any physical, structural or socioeconomic element to a natural hazard is its probability of being damaged, destroyed or lost. Vulnerability is not static but must be considered as a dynamic process, integrating changes and developments that alter and affect the probability of loss and damage of all the exposed elements." Using that schema, risk is defined as, "Risk can be related directly to the concept of disaster, given that it includes the total losses and damages that can be suffered after a natural hazard: dead and injured people, damage to property and interruption of activities. Risk implies a future potential condition, a function of the magnitude of the natural hazard and of the vulnerability of all the exposed elements in a determined moment" (Maskrey, 1989).

3.2.1 The Concept of Hazard - Definitions

Burton, Kates, and White (1978) explain hazards as an interaction between natural systems and human systems that can either create resources or hazards. Figure 6 illustrates that relationship between resources and hazards from nature and humans. For example, a flood or volcano may destroy farmland while fertilizing a field. The hazard is the risk encountered in occupying a place subject to flooding or volcanic eruptions. Under this model the natural systems are neither benevolent nor malicious and it neither prescribes nor sets constraints on what can be done with it. Humans transform the environment into resources and / or hazards, by using natural features for social,

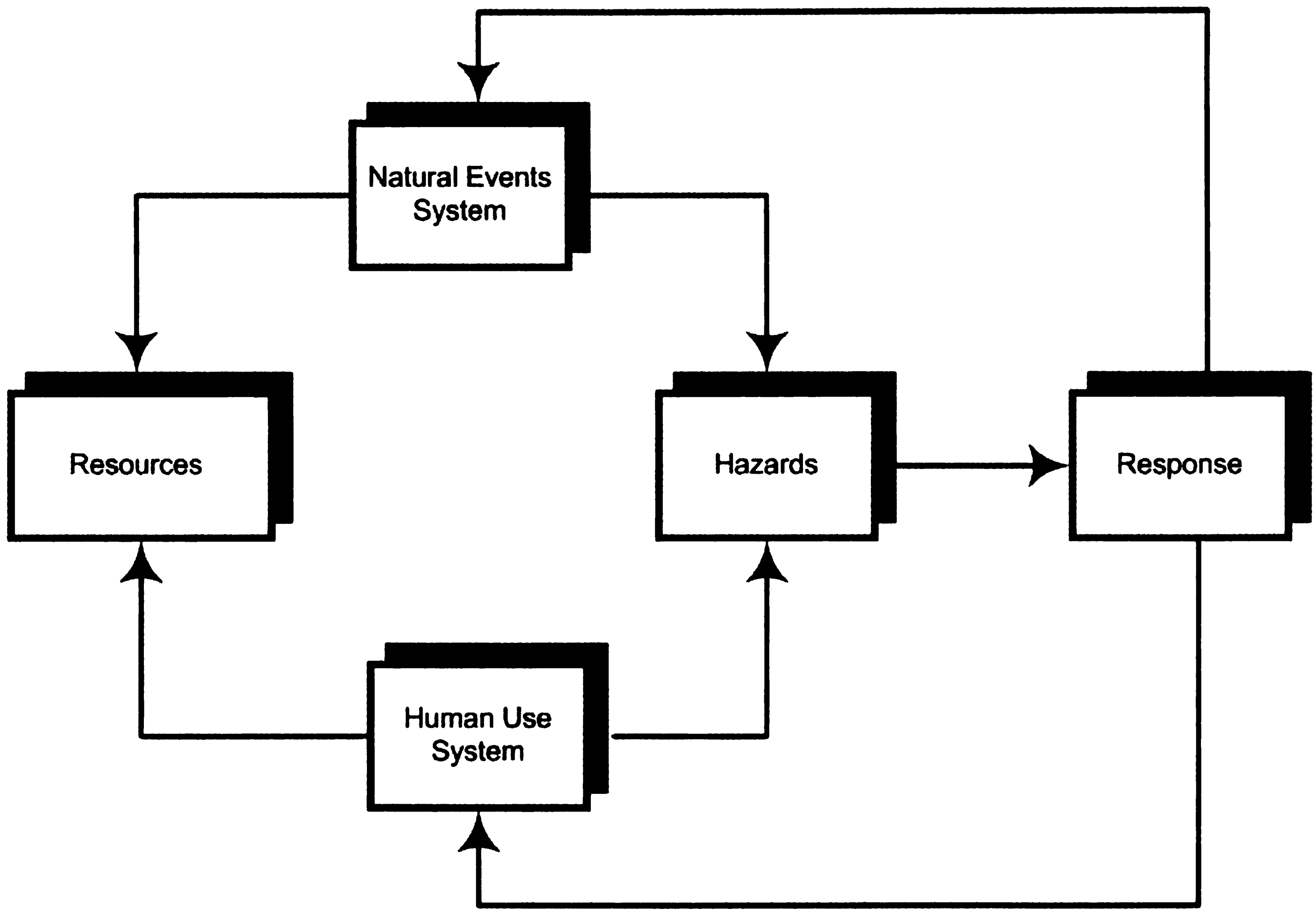

Figure 6. Environmental Hazards Interactions (Adapted from Burton, et al., 1978)

economic and aesthetic purposes (Burton et al., 1978). Using a similar approach, natural hazard can be defined as:

> "An interaction of man and nature, governed by the coexistent state of adjustment in the human use system and the state of nature in the natural events system" (Kates, 1971).

3.2.2 The Concept of Risk - Definitions

Risk has been defined as the likelihood, or more formally the probability, that a particular level of losses will be sustained by a given series of elements as a result of a given hazard impact (Alexander, 2000). The elements at risk consist of populations, communities, the built environment, the natural environment, and economic services that are under threat of disaster in a given area. Definition of total risk (Office of the United Nations Disaster Relief Coordinator., 1980) consists of the sum of predictable deaths, injuries, destruction, damage, disruption, and the costs of repair and mitigation. It can also be regarded as:

$$\text{Total risk} = (\Sigma \text{ elements at risk}) * (\text{hazard} * \text{vulnerability})$$

In this formula for risk, vulnerability is also a factor to consider. It loosely refers to a potential for losses or other adverse impacts. Vulnerability also refers to the potential for casualty, destruction, damage, disruption, or other forms of loss with respect to a particular hazard element. In some cases vulnerability and risk have been difficult to differentiate since risk creates a situation of vulnerability, whereas the existence of vulnerable elements in the light of known hazards poses a risk. Secondly, although the presence of vulnerability can usually be estimated without of knowledge of risk levels, it cannot be quantified without predicting the extent of damage and hence estimating the strength of the hazard is tantamount to estimating risk (Alexander, 2000).

Situations of environmental hazards can be considered as similar to other circumstances where modification or intensification of land use occurs during economic development activities, in that both situations stress the environment. Realistic risk assessment must be based on key indicators that effectively define the comparative developmental potential, environmental constraints, and anticipated economic and environmental effects (Schultink, 2001). In such risk assessments, Schultink suggested a modified risk equations to assess the composite indicator of environmental risk:

$$R_n = \sum_{i=1}^{n} r_n * p_n * v_n - t_n$$

Where:
r = the expected value of the magnitude or degree of risk
p = the exposure probability
v = the vulnerability of the target population
t = the potential risk reduction factor
n = the number of risk variables involved

This equation can be used to inform risk management activities that guide policy efforts to reduce risk through education, regulation, and mitigation.

Another framework in which to consider risk is to use the relationships between the severity of the environmental hazard, probability, and risk. Threats to human activity can be considered in terms of prioritization of severity. It is normally accepted that threats to human life are the most serious risk. Therefore, one way of prioritizing risk is:

1. hazards to people – death, injury, damage, stress
2. hazards to goods – property damage, economic losses
3. hazards to the environment – loss of flora and fauna, pollution, loss of amenity

The relationship between hazard and it probability can then be used to determine the overall degree of risk (Moore, 1983). Figure 7, adapted from Moore, illustrates the relationship. Using this construct, the highest dangers are associated with threats to human life, followed by threats to goods, and then threats to the environment.

This viewpoint represents an anthropocentric (or human-centered) perspective, founded in the dominant western industrial-scientific worldview. This dominant world view has been summarized by as (Catton and Dunlap, 1980):

1. People are fundamentally different from all other creatures on the Earth, over which they have dominion (defined as domination).
2. People are masters of their destiny; they can choose their goals and learn whatever is necessary to achieve them.
3. The world is vast, and thus provides unlimited opportunities for humans.
4. The history of humans is one of progress, for every problem there is a solution, and thus progress need never cease.

An ecologist provided some corollaries to this worldview, in terms of its approach to solving problems (Ehrenfeld, 1978):

1. All problems are soluble.
2. All problems are soluble by people.
3. Many problems are soluble by technology.
4. Those problems that are not soluble by technology, or by technology alone, have solutions in the social world (of politics, economics, etc.).
5. When the chips are down, we will all apply ourselves and work together for a solution before it is too late.

When considering disasters, they are a problem for people, and technological fixes can be applied to solve the problem. Much disaster research is therefore strictly based in the anthropocentric domain. This anthropocentric approach is reflected in the way that disasters are described, as on occasion one can find disasters referred in a context such as the battle against some type of natural phenomenon, as if humans are fighting against the flood or volcano. As the reach of technology is now global, and

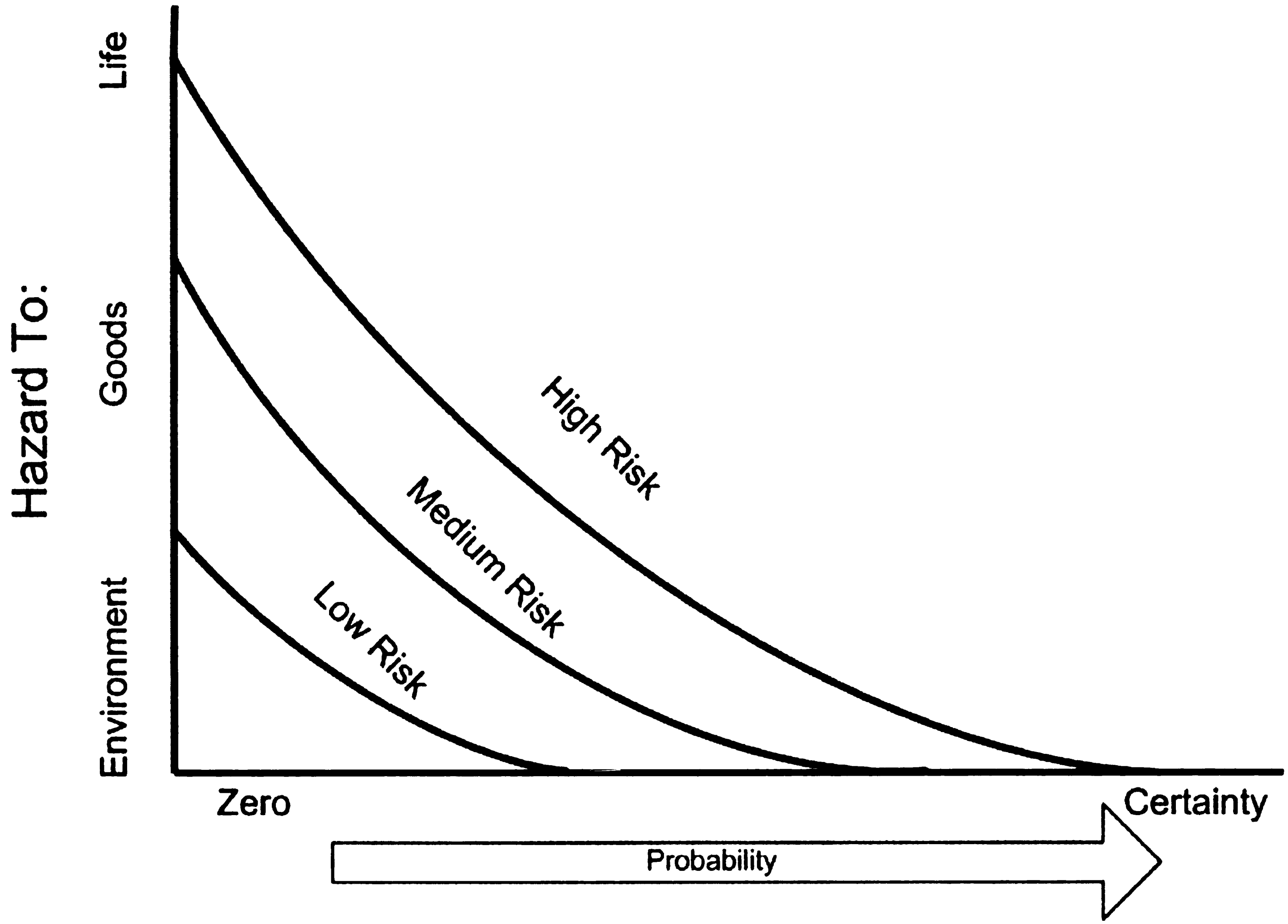

Figure 7. Theoretical Relationships Between Severity of the Environmental Hazard, Probability, and Risk (Adapted from Moore, 1983)

technology has the potential to alter to planet in ways which can induce 'natural' hazards (climate change), in order to understand disasters, it is necessary to realize when the anthropocentric perspective is being applied. In addressing environmental problems, anthropocentric thinking can sometimes complicate or worsen the situation, and the same may also apply to disaster problems.

3.2.3 The Concept of Disaster - Definitions

While disasters have been studied by social scientists and physical geographers for nearly seven decades, multiple foci have emerged from various fields. An anthropologist, Oliver-Smith states, "The definitional debate regarding disaster is significant because it prompts an exploration of the past and emerging dimensions of disaster in an increasingly hazardous present, as evidenced in new forms of hazard and rapidly changing human-environmental relations and conditions". (Oliver-Smith and Hoffman, 1999). This section of the literature review will comment on various aspects of the concept of disaster which are central to this study

In the 1970s, when the United States' first national assessment of natural hazards was completed, a commonly excepted definition of disaster was:

> "... an event, concentrated in time and space, in which a society, or a relatively self-sufficient subdivision of a society, undergoes severe danger and incurs losses to its members and physical appurtenances that the social structure is disrupted and fulfillment of all or some of the essential functions of society is prevented"(Fritz, 1971).

This functionalist viewpoint directed disaster research and strongly influenced national policy (Mileti, 1999). Much of the disaster research and policy during that time period focused on aspects preparedness and the immediate response after the disaster. This view of disaster draws strongly on sociology, based on research grounded in the strategic bombing studies of World War II. Much contemporary disaster research in the 1950s and

1960s was completed under the auspices of civil defense, as it was surmised that peacetime disasters include many physical impacts comparable to nuclear weapons effects. Therefore, natural disaster events could serve as laboratories for observing how individuals and communities cope with conditions of acute stress. That rationale has been continuously debated for years (Kreps, 1989). The Fritz definition has served the test of time since it balances attention to physical harm and social disruption, and it implies that different kinds of events involve social definitions of those unfavorable conditions (Barton, 1969). Sociologists interpret disasters as special types of societal phenomenon, in part because they are dramatically historical happenings (events), and also because they compel collective reactions (social catalysts) (Kreps, 1998).

Sociologists mostly have reached an implicit agreement about the definition of disaster. Approaches to studying disaster that range from examining how social systems react to physical harm or social disruption after an event has occurred, to examining what social systems do to mitigate the risk of physical harm and social disruption before the event occurs. Using either approach, disasters are thought to be implicit or explicit catalysts for collective action (Kreps, 1989).

Given these insights, Kreps alters Fritz's definition of disaster to:

> Non-routine events[21] in societies or their larger subsystems (e.g. regions, communities) that involve social disruption and physical harm. Among the key defining properties of such events are 1) the length of the forewarning, 2) the magnitude of the impact, 3) Scope of the impact 4) duration of the impact.

A key question in considering disaster is outlined by Oliver-Smith, as he asks if a disaster

[21] Kreps refers to non-routine events as, the phrase distinguishing disasters as unusual and dramatic happenings from the reservoir of everyday problems and concerns which confront mankind. For example, the fact that thousands of people die on American highways in any given year does not mean a disaster has been socially determined, while the crashing of a fully loaded airline in a central business district is more likely to be defined as a disaster.

is an identifiable phenomenon with an observable set of physical impacts or a subjective socially constructed process (Oliver-Smith & Hoffman, 1999) ? Following on the social construction aspects of disaster, one could ask whether any event with dislocating and disruptive events effects on humans is a disaster? What about the range of magnitude of disasters such as the economic distress of a plant closing or the health impacts of an epidemic? Such issues illustrate the interdisciplinary nature of considering disasters. An approach taken by Kreps attempts to balance social disruption, physical harm, and psychological dislocation. While this approach may be less inclusive, it still can incorporate a wide array of phenomena. He attempts to include both physical and social disruption, keeping boundaries broad to consider environmental, technological, and social events. Oliver-Smith comments that Kreps' broad-based approach would still exclude social phenomenon such as economic crises, plant closings, or computer failures unless they occasioned specific forms of destruction or mortality. It has been noted that including a wide variety of phenomenon under the rubric of disaster may tend to obscure important distinctions across classes of phenomenon.

Taking the sociological approaches a step further, there has been a call for a political ecological approach to disaster. A political ecology of disasters situates an ecologically grounded social scientific perspective within a political economic framework by focusing on relationships between people, the environment, and sociopolitical structures that characterize the society of which people are members (Campbell, 1996). The political ecological approach to disaster has been compared with development and environmental degradation both in development literature (Peet & Watts, 1993) and in disaster literature (Blaikie, 1994). Oliver-Smith summarizes the relationship by stating, a necessary but not sufficient condition for a disaster to occur is the conjecture of at least two factors: 1) a human population, and; 2) a potentially destructive agent. In this viewpoint, both society and the destructive agent are clearly causal phenomena, together defining disaster as a processual phenomenon rather than an event that is isolated in exact time frames (Oliver-Smith & Hoffman, 1999).

3.3 Key Concepts for Understanding Disaster Events

When a hazard is present, the risk is realized, and the hazard impacts a vulnerable population, a disaster takes place. While the disaster focused on this study is natural in origin, disasters can also originate from technological systems or social forces. When a disaster is realized, it is only one part of a cycle of events in what is known as the disaster cycle. This study focuses on one aspect of the disaster cycle, disaster recovery. Similar to the stages in the disaster cycle, disaster recovery also has its own sequence of events. This portion of the literature review will discuss two important concepts that help to differentiate between the different activities in a crisis event, the disaster cycle and the stages of disaster recovery.

3.3.1 The Disaster Cycle

The disaster life-cycle is depicted in Figure 8 (Schwab & American Planning Association., 1998). It is one of the key areas of the hazards literature which most emergency management practitioners are exposed to. There are four basic components of the disaster life cycle: response, recovery, preparedness, and mitigation.

During normalcy, there is *preparedness* before for a possible disaster. Preparedness is a basic building block of emergency management and it is defined as a state of readiness to respond to a disaster, crisis, or other type of emergency (Haddow and

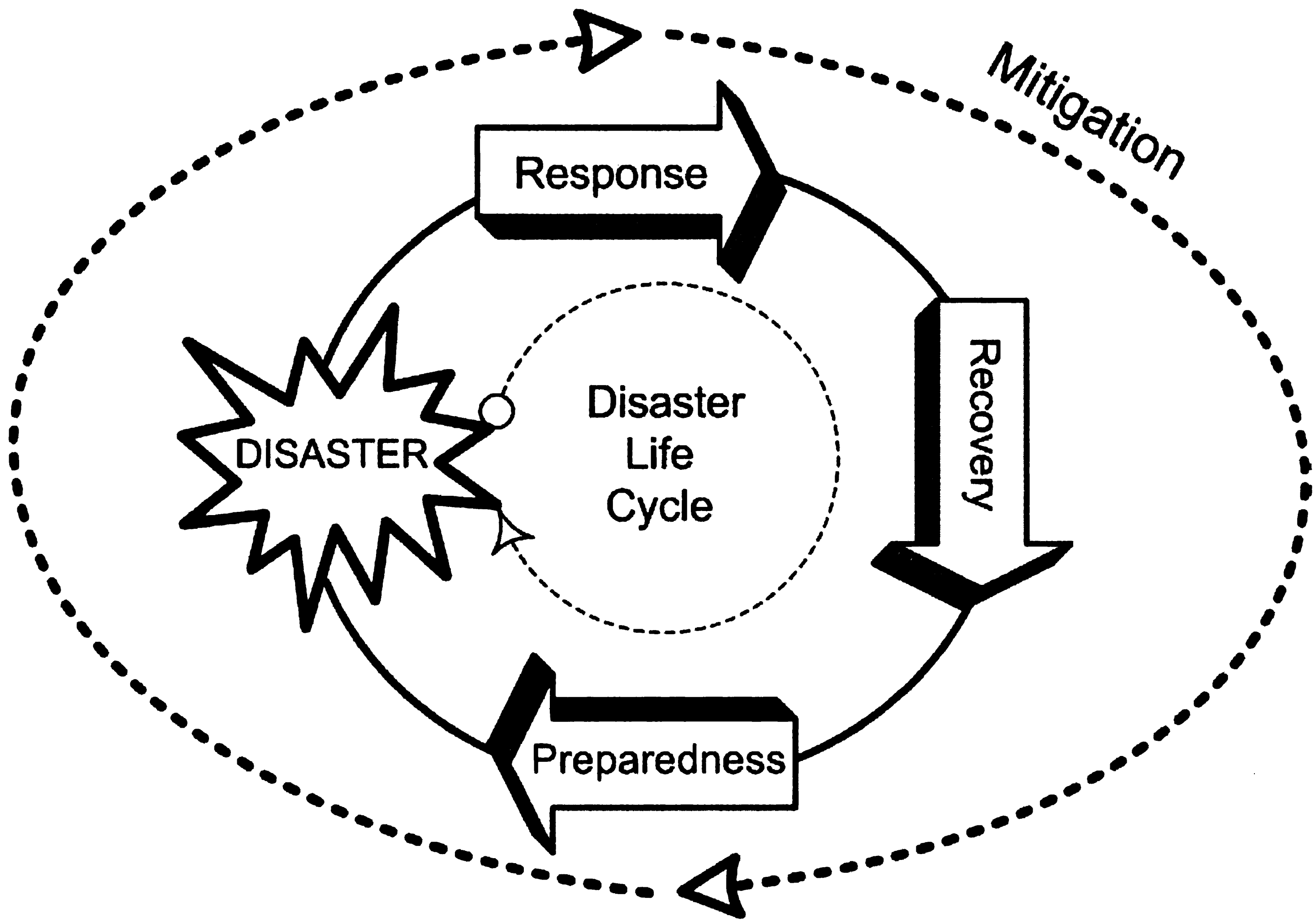

Figure 8. The Disaster Life Cycle (Adapted from Schwab and APA, 1998)

Bullock, 2003). Preparedness may include activities such as pre-disaster planning to assess vulnerabilities and the implementation of exercises where a mock disaster tests the response ability of the emergency management systems.

Then the *disaster event* occurs. A disaster is defined as a process / event involving a combination of a potentially destructive agent from a natural and/or technological environment and a population in a socially and technologically produced condition of environmental vulnerability (Oliver-Smith, 1996). While that disaster definition is comprehensive, it is important to note there are many perspectives on defining disaster as discussed in the previous section and as discussed by Quarantelli (Quarantelli, 1998).

Once the disaster occurs, the *emergency response* takes place. During the response police, fire, and medical personnel attend to the injured, suppress fires, secure and police the disaster area, and begin the process of restoring order (Haddow and Bullock, 2003). The response function has a singular focus on taking actions to meet basic human needs in the post-crisis environment.

As the crisis situation is stabilized to the extent possible, the *disaster recovery* begins. Recovery involves decisions and actions related to rebuilding homes, replacing destroyed property, resuming employment, restoring businesses and repairing and / or rebuilding infrastructure (Haddow and Bullock, 2003). Recovery is a unique phase of the disaster cycle as it requires the balancing of the need to return to normalcy with the imperative of reconstructing a community which is less vulnerable. The process of disaster recovery can be further subdivided into four periods; the emergency period (transition to recovery), the restoration period (patching), the reconstruction I period (replacement), and the reconstruction II period (developmental reconstruction) (Haas *et al.*, 1977). As disaster recovery is a main focus of this study, that concept is treated in greater detail in the next section.

Mitigation can take place at any time during preparedness, response, or recovery. Mitigation is defined as taking advanced action to reduce or eliminate long-term risks to human life and property from hazards (Godschalk, 1999). While mitigation activities can take place anytime before or after the disaster, in most cases mitigation activities are considered as separate from preparedness or response. Historically, disaster recovery has represented one of the best opportunities for mitigation as the most substantial funding for disaster mitigation has been provided during recovery activities. However, recent federal legislation, Disaster Mitigation Act of 2000[22], approved funding for pre-disaster mitigation that is not dependent on a federal disaster declaration (Haddow and Bullock, 2003). The Disaster Mitigation Act of 2000 is changing the way that pre-disaster planning takes place, as local emergency management officials and land use planners are now including hazard mitigation as a part of pre-disaster planning. Local hazard mitigation plans assess local hazard risks and suggest risk reduction actions (Tri-County Regional Planning Commission (Michigan), 2004).

3.3.2 Disaster Recovery

In an application of risk reduction strategies, Haas and Kates (1977) looked at comparative case studies of disasters in San Francisco, Anchorage, Managua, and Rapid City and wrote *Reconstruction Following Disaster* in which a process for the disaster recovery was suggested. This thinking was based on the premise that disaster recovery is

[22] Disaster Mitigation Act of 2000 (P.L. 106-390), enacted October 30, 2000.

ordered, knowledgeable, and predictable. The disaster recovery phase of the disaster life cycle can be subdivided into four parts as depicted in Figure 9.

The first or *emergency period* of disaster recovery is characterized by coping actions stemming from the high portion of capital stock that has been damaged or destroyed, and by the number of the dead, injured, homeless, or missing. During this period, normal social and economic activities cease or are drastically changed. Activities that indicate the closure of this period are the ending of search and rescue efforts, drastic reduction in emergency mass feeding and sheltering, and clearance of debris from major arteries (Haas et al., 1977).

The second or *restoration period* is characterized by patching of utility, housing, commercial, and industrial structures capable of being restored, and the return to relatively normal functioning of social and economic activities. Activities indicating the end of this phase of recovery include the functioning of major urban services, utilities, and transport, the return of the refugees who intend to return, and substantial clearing of rubble (Haas et al., 1977).

The third or *replacement and reconstruction period* is characterized by rebuilding capitol stock to pre-disaster levels and the return of social and economic activity to pre-disaster levels or greater. Activities indicating the end of this period include replacement of the population and the reconstruction to meet their needs in needs in terms of homes, jobs, capital stock, and urban activities (Haas et al., 1977).

The fourth or *betterment and developmental reconstruction period* is characterized by long-term community development and recovery. Activities during this period include memorializing or commemorating the disaster, marking the community's

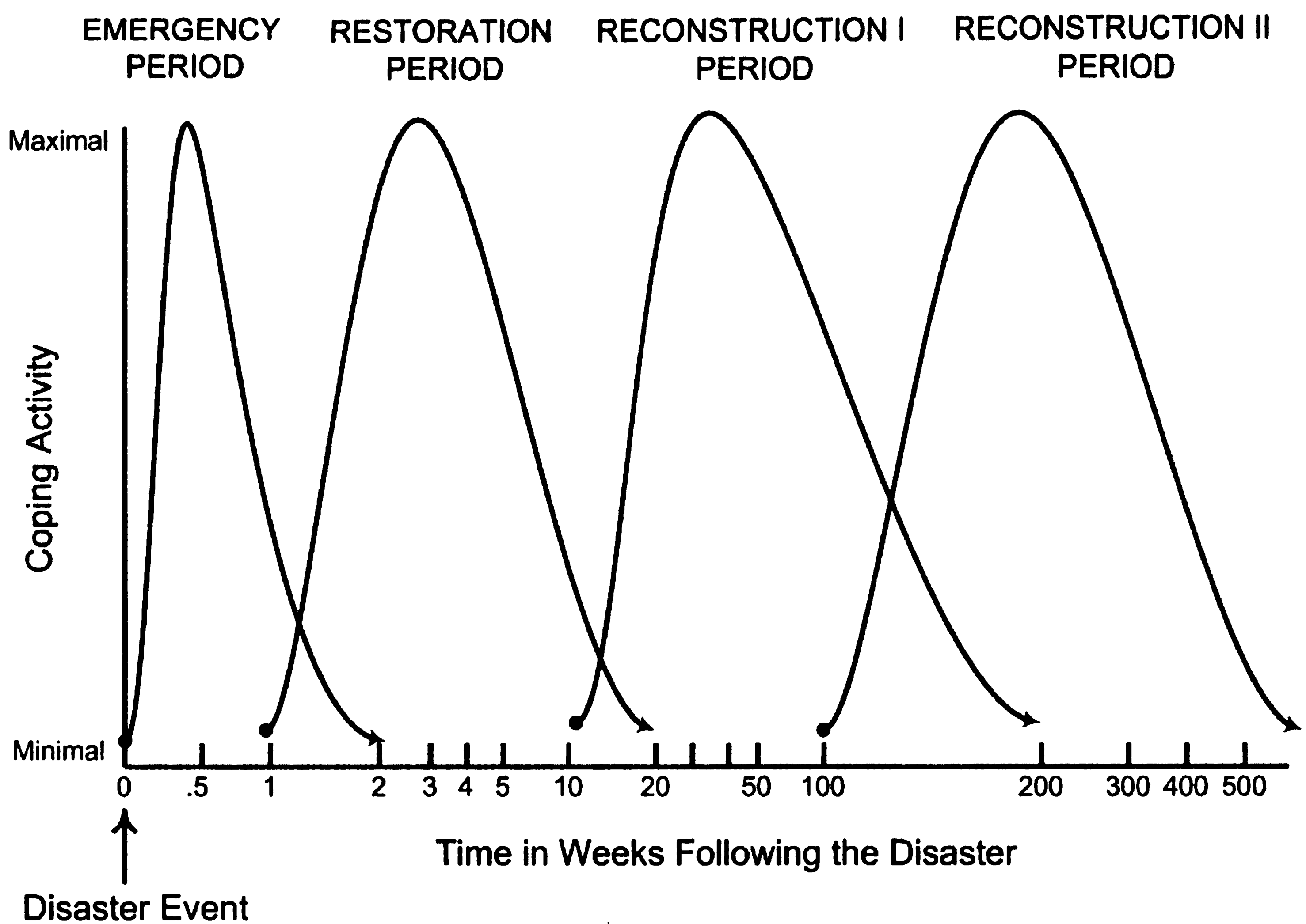

Figure 9. Four Phase Model of Disaster Recovery (Adapted from Haas, Kates, et al., 1977)

post-disaster improvement, and encouraging future growth and development (Haas et al., 1977). This period can go on for decades after the disaster.

Each of these stages lasts approximately ten times longer that the previous one, although many factors, such as a rapid reconstruction plan can shorten the time period between phases. The specific rate of recovery for any crisis is directly related to extent of the damage and the availability of the resources needed for recovery. While the four-period disaster recovery model was a significant contribution to the understanding of disasters, recent criticisms of that approach have developed.

In considering the disaster life cycle, the recovery phase has been the least investigated and the most poorly understood (Berke *et al.*, 1993). This research trend may be due to a number of factors. From the *research* perspective, much disaster research has focused on the preparedness activities, warnings before the disaster, and consequently on disaster operations during the emergency and restoration periods. The study of the replacement and reconstruction period and the community reconstruction and development can take many years. Research on long-term phenomenon represents many logistical problems. Such longitudinal research is rare, while shorter-term post-disaster case studies are more prevalent. Similarly, from the *practitioner* perspective, most disaster operations take place during the time frame immediately after the disaster. As illustrated in Figure 9, after a major disaster event it is suggested that most of the coping activity takes place during the first year after the disaster. As it is often the case, a disaster assistance team will move on to the next disaster (much like the researchers) relatively quickly. This situation leaves the longer-term portion of the recovery less practiced and less understood.

An article commenting on the recovery efforts still going on from Hurricane Mitch[23] in relation to the 2004 Asian tsunami brings the temporal aspect of disaster recovery into focus. While sympathetic to those persons affected by the Asian tsunami, in Honduras hurricane victims questioned how long the international aid efforts will be effective. In Honduras, three years after hurricane Mitch, 20,000 people were still homeless and living in shelters (Thompson & Fathi, 2005) . The article went on to highlight the problem:

> "But all too often when disaster strikes -- from here in Honduras to Iran, where the ancient city of Bam was shattered by an earthquake a year ago, to Mozambique, which endured floods in 2000 – that mission seems to last only as long as the media attention. After the last bodies are counted and public focus shifts, governments stop sending money, pledges are withdrawn, many private relief organizations pack their bags and the poor are left to finish reconstruction projects in the face of the same entrenched systems of corruption and neglect"(Thompson & Fathi, 2005) .

While the four period disaster recovery model has been useful in understanding the recovery from sudden onset singular events, in other ongoing disaster situations such a linear recovery model may not be adequate. Kelly has suggested that conceptualizing the relief-to-development continuum as linear is too simple as well as misleading (Kelly, 1998a). He suggests that protracted emergencies are sometimes the case where development and disaster can occur at the same time. The problem with the linear approach was also pointed out by Quarantelli and Hundley (1969), since their work highlighted the problem that decision making processes are often not orderly and linear. Community decision making is not strictly a technical exercise where each stage occurs in a proper sequence and then successful outcomes are guaranteed (Quarantelli & Hundley, 1970). Other studies also characterized the recovery process differently. In a

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[23] Hurricane Mitch hit Central America in 1999. Similar to the 2005, Tsunami, it was the unparalleled natural disaster of its time, spurring a large-scale international response.

study of fourteen disaster stricken communities, they found the four stages to be not necessarily sequential, but occurring simultaneously or in different sequences (Rubin *et al.*, 1985).

3.4 Review of Research on Hazards

As this literature review considers the risk assessment and hazards analysis paradigms, this section focuses on the hazards analysis paradigm by providing a literature review and context for the development of interdisciplinary research on hazards. This section starts with the initial human ecological approach to understanding hazards and links it to the geographical approach to hazards research. The hazard analysis paradigm is then described, and its critiques are reviewed with an emphasis on the sociological approaches to hazards research. Following from the sociological approaches to understanding hazards, the seminal work of the 1975 first hazards assessment, *Assessment of Research on Natural Hazards* is described. That assessment laid the foundation for the current interdisciplinary approach to hazards research, the refinements to the hazards adjustment paradigm, and the current developments in the thinking of how disaster recovery is described. These three areas of scholarship are especially relevant to this study. This literature review concludes with a discussion of the second assessment of natural hazards, completed in 1999, *Disasters by Design: A Reassessment of Natural Hazards in the United States* which advocates for a sustainable hazard mitigation approach for reducing disaster-related losses.

3.4.1 The Human Ecology Approach to Studying Hazards

In considering human interactions with environmental extremes, disasters cannot be considered truly 'natural' since human vulnerability seldom results from truly natural states. It has been argued that locational decisions based on socio-economic criteria and human intervention often result in a situation of aggravated risk of geophysical impact (Alexander, 1993). With contributions from both geography and sociology, the discipline of human ecology did not explain social context using only social facts, it included physical and biological facts as independent variables influencing social structure and other social phenomenon. Human ecology is based on the premise that humanity exists in a natural world that is innately hazardous resulting in human insecurity. Individuals and societies are thus compelled to seek security through the comfort of perceived absolute truths, such as religion, science, and philosophy (Dewey and Boydston, 1981). Dewey's perspective was that "Environmental problems stimulate inquiry and action which transform the environment, engendering further problems, inquiries, actions, and consequences in a potentially endless chain (Dewey, 1938)."

In the academic study of hazards during the twentieth century, natural hazards have been viewed as a result of interacting natural and social forces, a conception similar to Dewey's premise concerning environmental problems.

3.4.2 The Geographic Approach to Understanding Hazards

The basic underpinning of the hazards paradigm was reflected in Harlan Barrows' address to the American Association of Geographers in the 1920s (Cutter, 2001). Barrows' remarks titled "Geography as Human Ecology" suggested that both harmful and beneficial results are possible when society interacts with the physical environment. His work, during the 1920s, focused on human ecological adaptation to natural hazards where the relationship between people and their environment was viewed as a series of adjustments in both the human-use and natural-event systems (Barrows, 1923).

Gilbert White[24], a geographer, took the concepts of Barrows to the next level with his pioneering work on human adaptations to floods. His dissertation first asked the questions that still direct hazards inquiry today – Why are certain hazard adjustments preferred over others? (Mileti, 1999) White was one of the first to consider alternative flood-control solutions. After working for the Mississippi Valley Committee in the 1930s and for the Roosevelt administration in the early 1940s, he decided that careful study was needed to consider the range of possible actions that people could take with respect to flood hazards. White's 1945 monograph *Human Adjustments to Floods* argued that rather than trying to control floods, society would find it easier to stay out of floodplains altogether or to find productive uses for floodplains like planting only certain crops or using the flood hazard areas as recreational parks (White, 1945).

Following White, the geographical approach to hazards research now includes investigating how individuals and human collectives adapt to natural hazards by using adjustments. Adjustments can include activities such as mitigation activities such as implementing land use controls or re-engineering structures. Burton considered adjustments to be purposeful projects developed over a short-term time frame. Such projects are distinct from adaptations, that are longer-term cultural or biological coping measures that are often not the product of deliberate decisions of those who participate in them (Burton *et al.*, 1978). To reduce disaster losses, the geographical approach to hazards has emphasized better understanding the human-environment relationship to determine appropriate mitigation strategies.

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[24] Gilbert White is known as the father of natural hazards research.

3.4.3 Development and Refinement of the Natural Hazards Paradigm

Based on ideas from the geographical approach to hazards, the natural hazards paradigm emerged (White *et al.*, 1986). Cutter describes this concept as the "natural hazards analysis paradigm" that concentrates on five thematic areas (Cutter, 2001; Mileti, 1999):

1. Identification and mapping of human occupance of the hazard zone;
2. Identification of the full range of human adjustments to the hazard;
3. Study of how people perceive and estimate the occurrence of hazards;
4. Description of the process whereby mitigation measures are adopted, including the social context within which that adoption takes place;
5. Identification of the optimal set of adjustments to hazards and their social consequences

Refinements to the natural hazards analysis paradigm were illustrated in systematic explanations of the causal mechanisms for linking natural events and societal response. Two key models illustrating those mechanisms were the human adjustments to natural hazards model (Kates, 1971) and the human adjustment to environmental extremes model (Mileti, 1980).

3.4.4 Critique of and Alternatives to the Natural Hazards Paradigm

Critiques of the natural hazards paradigm concern the causal sequencing and explanations put forward about how individuals and societies adjust to hazards. Alternative approaches have suggested that other factors such as cultural, political, economic, and social forces have intensified hazards and made people more vulnerable (Blaikie, 1994). While the natural hazards paradigm has foundations in the school of thought known as human ecology, with much input from geographic and sociological approaches, it would be remiss not to also describe the "Disaster Research School" as outlined by Mileti (1999) and how it informs modern hazard and risk research.

Independent of the human ecology-based studies of environmental extremes, academic research on disasters also was greatly influenced by sociological research. Prince's 1920 dissertation research, "*Catastrophe and Social Change: Based Upon a Sociological Study of the Halifax Disaster*" was said to have been one of the first sociological inquiries into disaster. That study of the great Halifax explosion[25](Prince, 1920), led to other sociological studies into the nature and conditions of panic.

During the 1950s, increased disaster research was initiated by the Cold War. The research area of 'social disorganization' was developed to study disasters in order to attempt to the transfer lessons learned to civil defense activities. At that time, in the event of a nuclear attack, there was little information on which to base post-disaster planning and policy. Findings from that research have been incorporated into the social psychology of collective behavior and theories of social organization. In this sociological approach to studying disaster, vulnerability and impacts are considered in terms of human behavior and the effects of disasters on community functions and organizations (Dynes, 1970; Quarantelli, 1978).

The sociological approaches to disaster differ greatly from the approaches suggested by the human ecologists. Sociological studies of emergency planning put an emphasis on the importance of understanding both the social costs and possibilities for

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[25] The Great Halifax Explosion occurred on December 6, 1917. Two war ships, a Belgian relief ship, Imo, and a French ship carrying munitions, the Mont Blanc, fatally collided in Halifax Harbor. Incorrect signaling and misunderstanding between the two ships led the Imo to strike the side of the Mont Blanc. The Mont Blanc, which was carrying 400,000 pounds of TNT, 300 rounds of ammunitions, along with other explosive ingredients, caught fire and drifted closer into the city of Halifax. Before the fire could be put out, the Mont Blanc exploded creating the "biggest man-made explosion before the nuclear age". The explosion killed over 2,000 people and injured 9,000. The explosion caused $28 million in damage - 326 acres of the north-end of Halifax's waterfront had been destroyed. (from Macalester College Geography Department website, available at http://www.macalester.edu/courses/geog61/ahannert/halifaxdisaster.html)

effective social action (Dynes, 1993). Collective behaviorists and scholars of social organization found that after impact, disasters were found to strengthen rather than paralyze the effected communities (Mileti, 1999). Beyond the disaster impact studies, sociological inquiries into disaster have also covered various topics ranging from warning systems to ethnic and racial inequalities in community recovery (Peacock *et al.*, 1997). In general, to reduce disaster losses the sociological approach to hazards has emphasized upgrading disaster preparedness and emergency response.

3.4.5 The First National Assessment of Hazards

In the early 1970s, natural hazards research was spotty, uncoordinated, and dominated by the physical and technological fields. The state of social research on hazards was sporadic and driven by interests of individual investigators and missions of specific agencies. Furthermore, while knowledge had been advanced in specific domains, no broad body of knowledge had been created (White & Haas, 1975).

The dominant approaches for hazards research were entrenched in either the geographic perspective or the sociological perspective. While the geographical perspective had its background in human ecology stressing loss reduction, the sociological perspective had its background in collective behavior stressing disaster preparedness and emergency response. Clearly, the study of disaster also encompasses a myriad of fields including, climatology, economics, engineering, law, geology, planning, public policy, psychology, meteorology, and seismology.

Given this situation, geographer Gilbert White and sociologist Eugene Haas led a team to create the nation's first assessment of research on natural hazards. The purpose of the assessment was to take stock of the nation's knowledge regarding natural hazards and disasters with an emphasis on the social sciences to suggest directions for national policy and to inventory future research needs.

The main achievement of the 1975 *Assessment of Research on Natural Hazards* was to pave the way for cooperation between researchers taking either the geographic or sociological approach. The project lowered the walls that had separated many of the disciplines involved in natural hazards research. Mileti suggests that a new hazards paradigm did not emerge but, a shared more integrated approach did. He described it as:

> "Planners incorporated a sociological perspective on human adjustment in the geographical / human ecological tradition; geographers conducted research on societal response to disasters; seismologists learned the social psychology of risk communication; social scientists conducted risk analyses; engineers worked to understand the social science dimensions of technology transfer; and public administrators drew on the knowledge of all disciplines"(Mileti, 1999).

3.4.6 Refinement of the Hazards Adjustment Paradigm

Since the nation's first hazard assessment, theoretical, empirical, and policy work concerning hazards has been based on the notion that human beings as individuals and in groups such as families, communities, and businesses choose how they cope with or adjust to extremes. This general approach to dealing with hazards is known as the hazards adjustment paradigm (Mileti, 1999).

In the hazards adjustment paradigm, natural hazards are defined as extreme, low probability meteorological or geological phenomenon that have the potential to cause disasters when they strike human collectives. This paradigm applies the bounded rationality model of individual decision making which says that individuals make decisions based on limited knowledge within constraints of their social system.

The bounded rationality decision making model coupled with the hazards adjustment concept resulted in a five step model for considering coping with hazards (Mileti, 1999). The five steps are:

1) Assess hazard vulnerability
2) Examine possible adjustments
3) Determine the human perception and estimation of the hazard
4) Analyze the decision making process
5) Identify the best adjustments, given social constraints, and evaluate their effectiveness

These five steps are very similar in concept to what Cutter describes as the basis for the 'natural hazards analysis paradigm'. Risk reduction strategies have been developed around these five steps.

3.4.7 The Second Hazards Assessment

In the 1990s, Dennis Mileti (at the University of Colorado's Natural Hazard Research and Applications Center) led an effort to create the nation's Second Hazards Assessment. *Disasters by Design: A Reassessment of Natural Hazards in the United States*, stressed a sustainable hazard mitigation paradigm. While it was concluded there was no need to abandon approaches that have been refined since 1975 hazards assessment (the natural hazards paradigm and the hazards adjustment approach to coping with crisis), disaster-related losses continued to mount. Notably, from 1989 to 1994, seven of the ten most costly disasters (based on dollar losses) in United States history occurred.[26] During this time period, the nation encountered periods where catastrophic

[26] These seven of the ten most costly disasters in the United States from 1989 to 1994 were: 1989 - Hurricane Hugo ($9 Billion in disaster related losses), and the Loma Prieta Earthquake ($7 Billion in disaster related losses); 1991 - California Wildfires ($1.5 billion in disaster related losses); 1992 – Hurricane Andrew ($30 billion in disaster related losses), and Hurricane Iniki ($1.8 billion in disaster related losses); 1993 – Mississippi River Flood Disaster ($12-$16 billion in disaster related losses); 1994 – Northridge Earthquake ($28 billion in disaster related losses)

losses from hazards averaged about one billion dollars per week. Such drastic losses are expected to continue into the foreseeable future (Mileti, 1999).

The second hazards assessment was driven by three concepts. Those concepts were:

1) The already staggering monetary losses from disaster are still increasing.

2) There are no reasons to believe that mitigation activities are simply postponing losses that will be more catastrophic when they do occur.

3) Many efforts at disaster mitigation, along with many new disasters, have resulted in short-term cumulative imbalances of environmental degradation and ecological imbalance. Besides being detrimental to society, these factors also contribute to the occurrence and severity of the next disaster

The second hazard assessment advances a sustainable hazards mitigation agenda. Sustainable hazards mitigation embraces the hazards adjustment paradigm, but takes it further with a long-term goal to foster mitigation and loss reduction and to avoid burdening future generations with unnecessary hazards. The goal of the sustainable hazards mitigation approach is not just to reduce losses but to build local sustainable communities with an eye toward expanding that resiliency to the national and international sphere. This concept of sustainable hazards mitigation has six essential components (Mileti, 1999):

1. Maintain and enhance environmental quality
2. Maintain and enhance people's quality of life
3. Foster local resiliency and responsibility
4. Support a local economy by using mitigation actions do not detract from the economy
5. Ensure inter- and intra-generational equity in the selection of mitigation options
6. Adopt local consensus building

While the hazards research community mostly embraces the approaches forwarded in the second hazards assessment, some have questioned the practicality of its wide ranging agenda. Cutter has noted that "While the Second Assessment sets out wide ranging goals, many of these may not be realistic or achievable, given contemporary political and economic priorities." However she goes on to state, "On the other hand, there may be no better place to begin the process of restructuring nature – society interactions (Cutter, 2001)."

3.5 A Review of Risk Research Risk in the Context of Hazard

Hazard and risk are sometimes viewed as synonymous terms. While they are related to one another, this section of the literature review will explain hazard and risk in the context of one another, with a focus the aspects of risk research relevant to this study.

One widely accepted view of hazard and risk has been proposed by Smith (1996). Hazard has been defined as a naturally occurring or human induced process or event with the potential to create loss, i.e. a general source of danger. Risk has those same implications, and in addition it has the implication of the chance of the particular event occurring. Risk is the actual exposure of something of human value to a hazard, and it is often regarded as the combination of probability and loss. Using these terms as a departure point for considering risk, we can define hazard (cause) as 'a potential threat to humans and their welfare' and risk (consequence) as 'the probability of a specific hazard occurrence' (Smith, 1996). While pointed out earlier in this chapter that disaster has many rich meanings, following the concepts of hazard and risk as defined above, disaster would then be defined as a ' realization of the hazard'. However, there is no universally agreed upon definition of the scale on which the loss has to occur in order to qualify as a disaster (Smith, 1996).

This portion of the literature review will focus on relevant aspects of risk research such as risk and risk mitigation, risk communication, and risk assessment.

3.5.1 Risk and Risk Mitigation

When considering how social units adopt policy to mitigate the risk of environmental extremes, Slovic (1974) proposed a four step process. In this process, first a social unit (the individual or society) assesses the probability of a natural environmental extreme. Second, a review of adjustment policies available to mitigate risks takes place. Third, an evaluation of the impacts of these alternative adjustment strategies with reference to both risk abatement and potential consequences for other aspects of social life occurs. Fourth, a choice is made to implement one or none of the risk mitigation adjustment policies (Slovic & Kunreuther, 1974). Mileti has commented that this four step process is often altered by other factors such as a less than accurate appraisal of risk, inadequate knowledge about the effectiveness of a particular adjustment policy, bias in the processing of information, self-serving decisions, and other factors (Mileti, 1980).

Based on the work of Burton et al. (1978), Mileti illustrated a theoretical feedback model illustrating how social systems and human actors are capable of continually adjusting to changes in the physical world. Figure 10 illustrates that model of the theory of risk mitigating adjustment.

In this model of risk mitigating adjustments, human use systems and varied forms of social organization act in concert with physical systems to define level of risk. For example, in cases of land use practices promoting development within the geographical extent of the floodplain, the probability of flooding will define the risk level. In this case, risk is defined as the chance that a physical system will exceed some normal level and

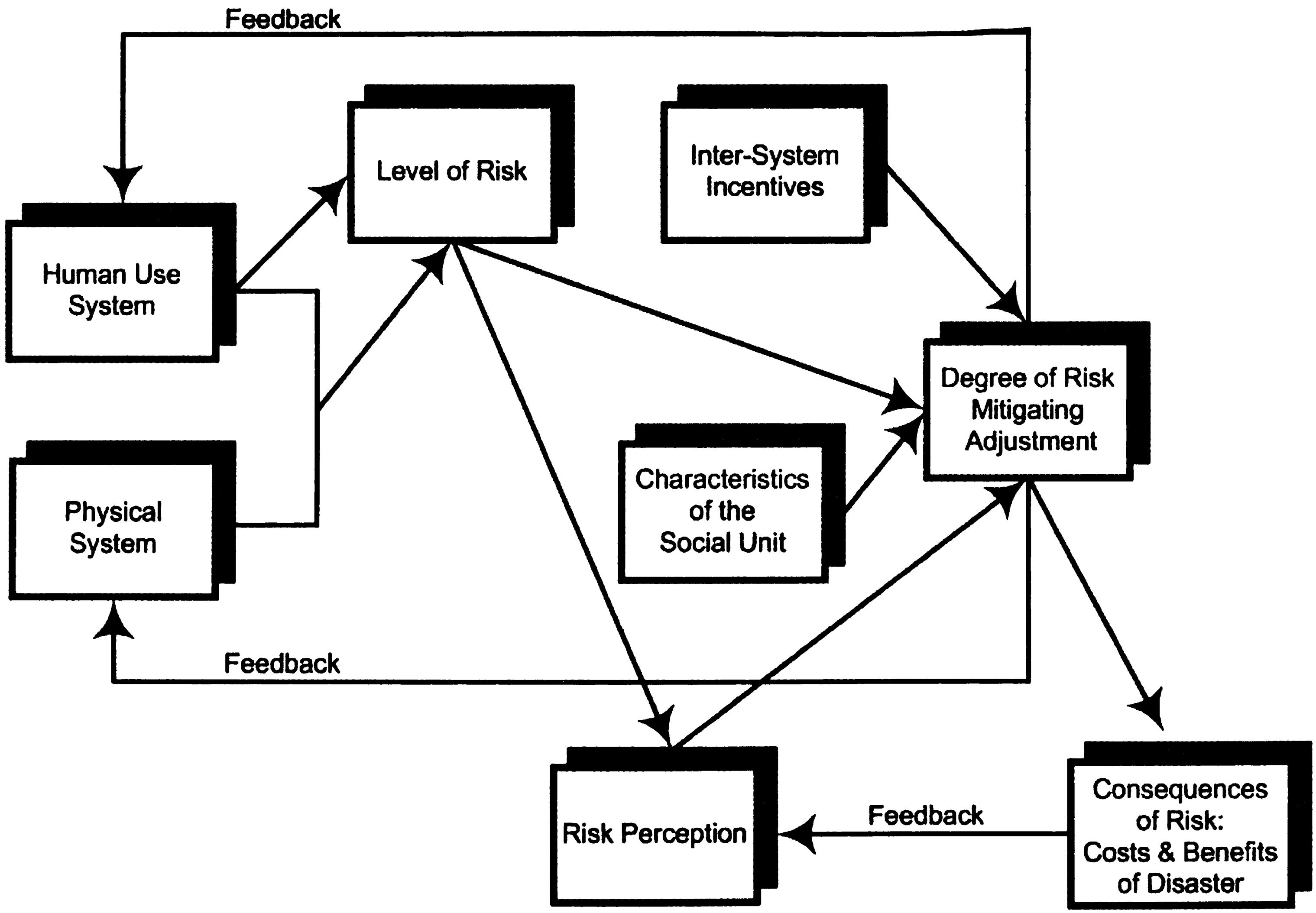

Figure 10. Theory of Risk Mitigating Adjustment (Adapted from Mileti, 1980)

cause harm to people. Geophysical characteristics and human uses of the land determine exposure to risk. Actions or adjustments taken to avoid flood risk determine the level to which risk has been reduced. All of these factors determine the net risk exposure of the human aggregate to the environmental extreme (Mileti, 1980).

Figure 10 illustrates the key roles of three categories that play roles in affecting adjustments to environmental extremes. The three categories are risk perception, characteristics of the social unit, and inter-system incentives.

Perceived risk, is the cognition or belief in the seriousness of the threat of the environmental extreme, as well as the subjective possibility of experiencing an environmental extreme (Kunreuther, 1978). Characteristics of social units play major roles in determining whether policy is implemented. They include the perceived cost of policy implementation based on social values and interest group goals (Sorensen & White, 1976), and the capacity of the social unit to implement the policy under determination, largely determined by aspects of structure including social, power, and political differentiation (Dynes & Wenger, 1971). Inter-system incentives refer to policy and regulations implemented at larger levels of human aggregation, which perceive greater risk at smaller levels of human aggregation. In other words, governmental policies and regulations define the character of inter-system incentives to enhance adjustment to environmental extremes. A three class typology of these incentives has been defined as 1) information, 2) incentives, or economic power to alter the incentive structure through payments or penalties, and 3) command or regulation to compel performance (Braybrooke & Lindblom, 1963).

The model of risk mitigating adjustments to humans is useful because it illustrates that a variety of policies can be installed to accomplished adjustments. To reduce risk from disaster emergency preparedness can be increased or human vulnerability can be reduced. Risk mitigating adjustments cut across technological, cultural, redistributional, and regulatory mechanisms. They include actions that are purposeful – like changing use and reducing or accepting losses – and those that are incidental, along with unwitting adaptations (Mileti, 1980).

3.5.2 Risk Perception

Within a social scientific framework, risk perception denotes the process by which people receive and process physical signals as well as information about possible outcomes of human actions or natural events (Renn, 1991).

In reviewing literature on risk perception, I will approach the concept from the viewpoint of the social scientific approaches to risk management. The literature defines two approaches for the social scientific approach to risk management. One approach is known as the psychometric paradigm, while the other school of thought is based more on experiential factors and 'Chicago School' of geography.

The 'Chicago School' approach is based on the research of Gilbert F. White. He investigated people's response to natural hazards in floodplain areas and proposed that reaction to hazards and the degree to which people exposure themselves to risk is based on experiential factors (White, 1945). Burton and Kates later expanded this understanding of risk in comparing the occupance of different hazard zones (Burton & Kates, 1964). Much of this research is still relevant to natural hazard studies today, as explained in greater detail in hazards sections of this literature review.

A key model in understanding risk perception is the psychometric paradigm. It is based on psychologists' response to the work of an engineer, Starr, in the late-1960s. Starr's 1969 article, *Social Benefit vs. Technological Risk*, investigated society's previous response to risk in terms of the critical issue of whether or not responses to risk were voluntary. He began to probe the question 'how safe is safe' (Starr, 1969)? His research found that by trial and error society will arrive at an 'essential optimum' balance between the risks and benefits associated with any activity. The merits and deficiencies of that approach have since been the subject of debate. However, that work was the original impetus for the psychometric paradigm.

The psychometric paradigm is a broad strategy for studying perceived risk by developing a taxonomy scheme that can explain why some people have extreme aversion to some hazards, indifference to others, and discrepancies between those reactions and the opinions of experts (Slovic, 2000). That strategy uses psychosocial scaling and multivariate analysis techniques to produce quantitative representations and cognitive maps of risks, perceptions, and attitudes.

An important model was developed by Slovic, Fischhoff, and Lichtenstein to represent the relationships between perceptions, behavior, and qualitative characteristics of hazards (Slovic & Fischoff, 1980). The factor analytical model is represented in Figure 11. In this 1987 model, the location of 81 hazards on factor 1 (dread risk[27]) and 2 (unknown risk[28]) derived from the interrelationships of 15 risk characteristics. Figure 12 illustrates the combinations of characteristics. Applications of this model have indicated

[27] Dread risk is defined by a perceived lack of control, catastrophic potential, fatal consequences, and the inequitable distribution of risks and benefits. Nuclear weapons rank high in that category.
[28] Unknown risk is defined as hazards judged to be unobservable, unknown, new, and delayed in their manifestation of harm. DNA technology ranks high in that category.

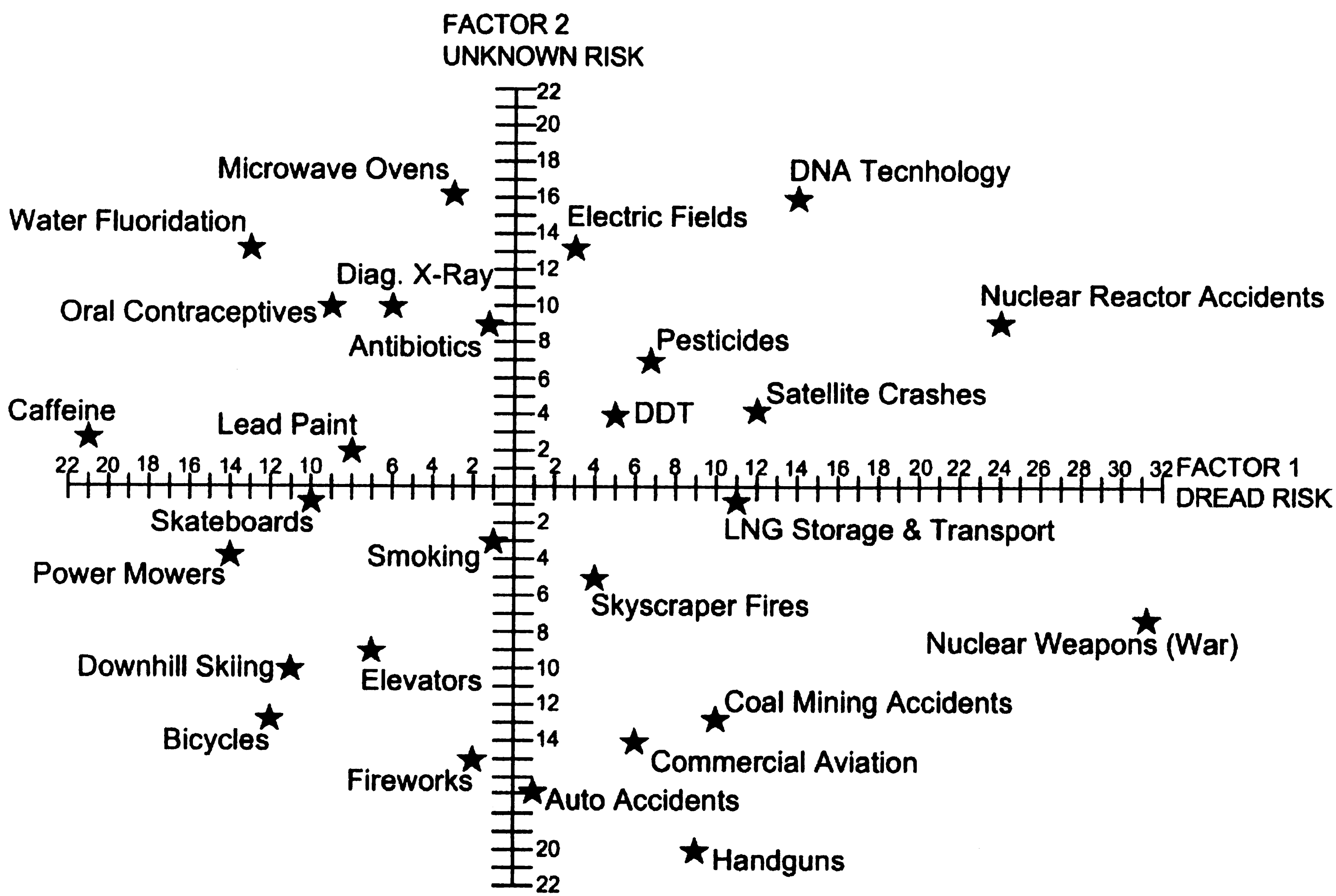

Figure 11. The Factor Analytical Model of Risk Perception (Adapted from Slovic, 1987)

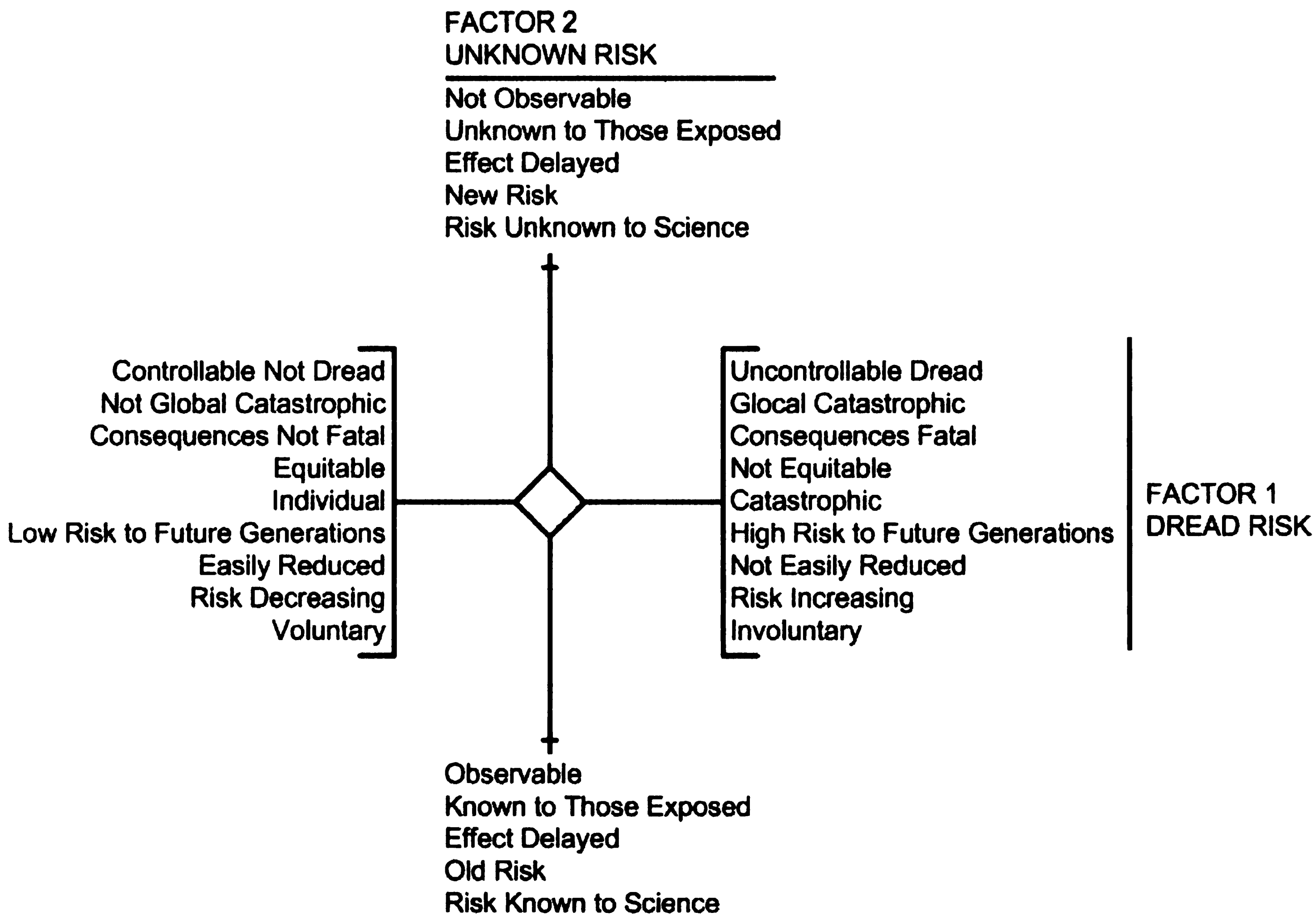

Figure 12. Combinations of Characteristics for the Factor Analytical Model (Adapted from Slovic, 1987)

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that higher a hazard's 'dread risk', the more likely it will be a perceived risk. In that case, people will want to see the risks reduced, and they will be more likely to support strict regulation to achieve the desired reduction in risk (Slovic, 2000). While this risk perception model is by no means universal, it important in the literature and applicable to understanding extreme environmental events.

3.5.2.1 Risk Communication and the Social Amplification of Risk

Following on the concepts of the risk perception, this section of the literature review addresses risk communication, specifically the concept of the social amplification of risk.

In general, risk communications principles have been used in variety of public contexts to alert the public to issues ranging from the mundane, like traffic advisories, to the extreme, like accidental hazardous chemical releases. An outcome of understanding risk perception is the development of effective risk communications about different potential hazards. While risk communication cannot be defined as an independent discipline, it is described as the flow of information and risk evaluation, back and forth, between academic experts, regulatory practitioners, interests groups, and the general public (Leiss, 1996). Slovic has commented that while descriptive literature on risk communication can help to predict which issues will get out of hand or escape needed attention – it does so in the absence of deliberate competent communications (Slovic, 1987). Fischoff also comments that simple (communication) skills are often essential to executing sophisticated plans (Fischoff, 1995).

When considering the area of risk communication, it is first necessary to develop a conceptual framework which incorporates the various factors that determine effective risk cor

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risk communications. One important aspect of this literature review focuses on the social amplification of risk.

The social amplification of risk theory takes into account the integration of different models of risk perception and risk communication (Kasperson & Renn, 1988). Renn explains the social amplification of risk theory as:

> "Based on the thesis that events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that can heighten or attenuate individual social perceptions of risk and shape risk behavior" (Renn, 1991).

These processes start with some kind of risk event being realized, and then that event is selected by a transmitter of the information (for example mass media) which amplifies or attenuates the risk. The risk message is then transmitted again by members of society who might again amplify or attenuate the risk into a message. The message can then lead to secondary effects. The concept of amplification is taken straight from communications theory (DeFleur, 1966), where it denotes a process of intensifying or attenuating signals during the transmission of information from an information source - to intermediate transmitters - and finally to a receiver. However, the process of transmitting is more complex than the electronic metaphor implies, since messages have a meaning for the receiver only within a socio-cultural context (Kasperson & Renn, 1988).

The representation of the social amplification of risk is presented as a diagram in Figure 13, which depicts the phenomenon by which information flow, institutional structures, social-group behavior, and individual responses shape the social experiences of risk, thereby contributing to risk consequences.

While this model has been applied to better understand communications involving technological risk, it has also received some criticisms as being too simple in its

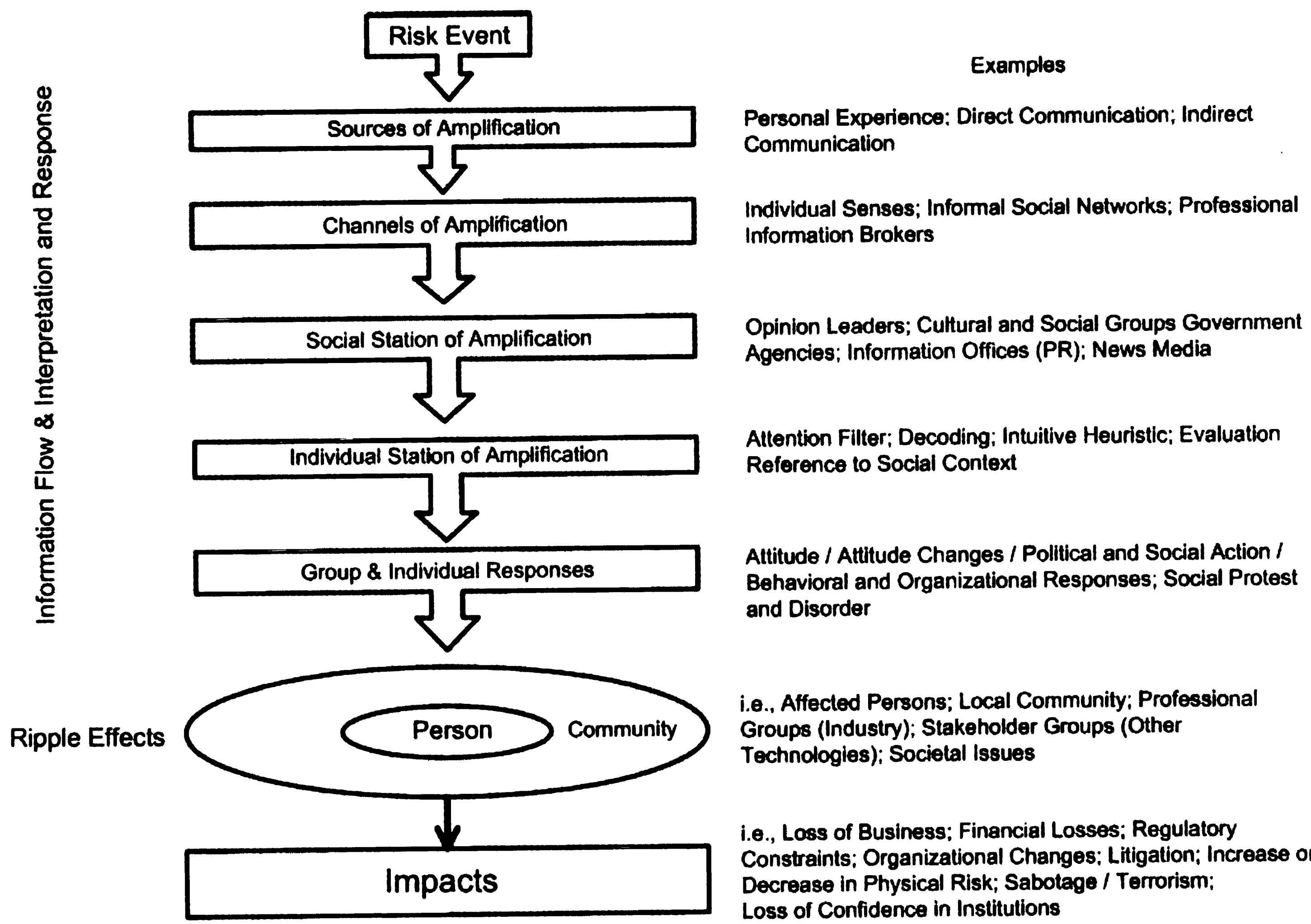

Figure 13. Representation of the Social Amplification of Risk
(Adapted from Kasperson, Renn, et al., 1988)

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explanation of the mechanisms of risk amplification and risk attenuation. Renn (1991) also points out that the process of amplification or attenuation in itself is likely to provoke further responses, creating feedback within the process. He states that feedback is an area that needs to be further explored.

Despite these critiques, the social amplification of risk concept is the beginning of a framework to build a comprehensive theory that explains why seemingly minor risks (or events) often produce extraordinary public concern and social and economic impacts, with rippling effects across time across time, space, and social institutions (Kasperson & Renn, 1988).

3.5.3 Risk Assessment

Risk assessment includes the identification, measurement, and characterization of threats to human welfare (Barry *et al.*, 1991). In reviewing the literature concerning risk assessment, many applications of risk assessment were related to the work of the Federal Government in terms of assessing potential risks of technologies (such as nuclear energy, e.g. Three Mile Island) and in determining environmental impacts (various U.S. Environmental Protection Agency pollution control initiatives). Much of the risk assessment literature focuses on very narrow aspects of risk characterization for the purposes of quantifying the characteristics of threats from environmental pollutants.

When addressing risk assessment here, a broader view of the concept is taken similar to the context of ecological risk assessment. The general framework for risk assessment consists of five policy steps (Cunningham & Cooper, 1998):

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1. Hazards Assessment, demonstrating the links between human actions and adverse effects

2. Dose-Response Relationships, often used to describe the toxicity of chemicals based on human studies (including clinical and epidemiological approaches)

3. Exposure Assessment, identifying the population, detailing the level, duration, and frequency of exposure

4. Risk Characterization, determining the overall risk, preferably including quantification of uncertainty

5. Risk Management, the final decision-making step encompassing administrative, political, and economic actions taken to decide if and how a societal risk is to be reduced to a certain level and at what cost.

Steps one to four consist of the scientific component of risk assessment while step five resides in the socio-political realm. This formal risk assessment approach was accepted in 1983 when the National Research Council published *Risk Assessment in the Federal Government: Managing the Process* (Committee on the Institutional Means for Assessment of Risks to Public Health., 1983), a report that systematized definitions and concepts as well as presenting the four step scientific component risk assessment framework (Cutter, 2001). The ultimate goal of this type of risk assessment was to identify remedial options for environmental pollution problems that posed a threat to human and ecosystem health. In the late 1980s, the U.S. Environmental Protection Agency compared the risks of environmental problems under their jurisdiction using four dimensions[29]. As a result of this comparison risks were rank-ordered. This type of assessment differed from the probability-based assessments that were previously the standard (Office of Policy Analysis., 1987). This relative-risk approach led to a change in emphasis within the agency – a movement away from pollution control and

[29] The four dimensions used to compare environmental risks were human cancer risk, non-cancer human health risk, ecological risk, and welfare risks.

technological fixes, and more focus on risk reduction and sustainable approaches to pollution management (Cutter, 2001).

Ecological risk assessments are similar to human health assessments, but they estimate the severity and extent of ecological effects associated with an exposure to an anthropogenic agent or perturbational change. Ecological risk assessments are more complex than the scientific risk assessment approach. Ecosystem assessments have more complex interactions, they attempt to replicate often poorly understood mechanisms, and multiple feedback loops are present.

Ecological risk assessment moves beyond narrowly conceived applications of risk assessment to consider larger multidisciplinary environmental issues such as global climate change, loss of biodiversity, acid rain, and effects of multiple chemicals on ecological systems. Such complex problems highlight the need for a flexible problem solving approach that can link ecological measurements and data with the decision making needs of environmental managers. The U.S. Environmental Protection Agency's *Proposed Guidelines for Ecological Risk Assessment*, (Risk Assessment Forum., 1996) suggest a broad based risk assessment framework. Figure 14 illustrates that ecological risk assessment framework.

Since the ecological risk assessment procedure has been developed, research has been done to further make the risk assessment enterprise more interdisciplinary. While differences in receptors and endpoints remain to be a concern, an integrated risk assessment has been proposed that integrates health and ecological risk assessment. Integrated risk assessment seeks to bridge gaps between physical and social elements of risk (Center for Integrated Risk Assessment., 2004).

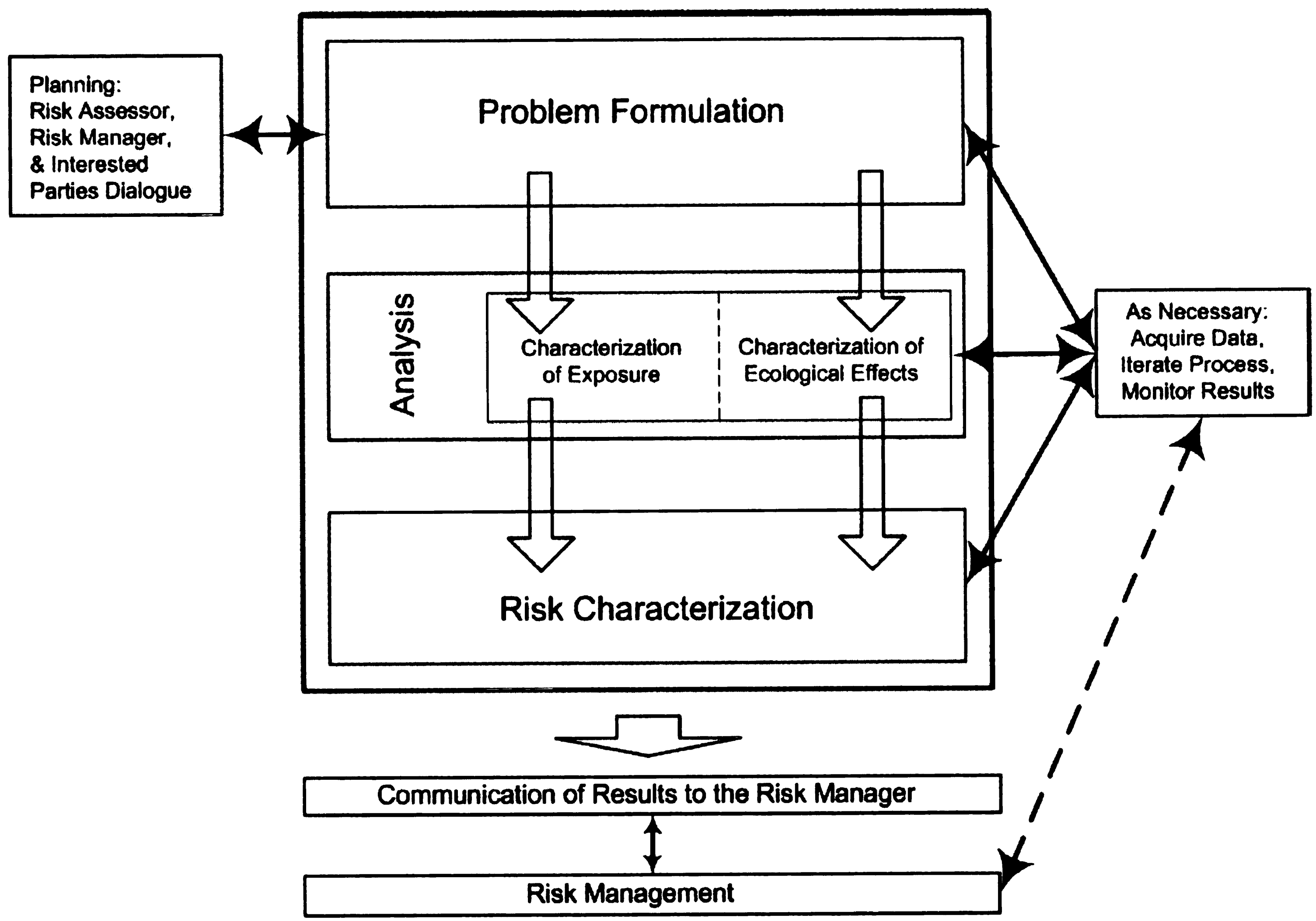

Figure 14. Ecological Risk Assessment Framework
(Adapted from U.S. Environmental Protection Agency, 1996)

When considering risk assessment in relation to natural hazards, Kates has established a model that illustrates the relationship between the elements of risk assessment he defines as identification, estimation, and evaluation. Kates' model as represented by intersected circles (see Figure 15) indicates that elements of risk overlap considerably both in concept and practice. As depicted in Figure 15, hazard identification is the recognition of a hazard – providing the answer to the question of what constitutes the threat. Its methods are the methods of research, screening, monitoring and diagnosis. Risk estimation is the measurement of the threat potential of the hazard – providing the answer to the questions of 'how great are the consequences?', and 'how often do the events occur?'. Its methods of knowing are revelation, intuition, and extrapolation from experience. Societal evaluation is the meaning attributed to the measurement of threat potential, answering the question of 'how important is the estimated risk?' Its methods include comparison: aversion, balance, and benefit-cost analysis (Kates and Scientific Committee on Problems of the Environment., 1978).

3.6 Conclusion to Literature Review

As illustrated in this review of literature, despite overlaps in the field of disaster, hazard, and risk, each field still has its own distinct foundations. White (1988) observed that there is surprisingly little communication between hazards researchers and the risk analysis community. This is partly a function of the focus on extreme events by the hazards community, whereas the risk assessment community was initially more interested in technological risks and industrial failures (Cutter, 2001). Another explanation suggests that risk analysis fails to include the social structure or social context in which risks occur (White, 1988).

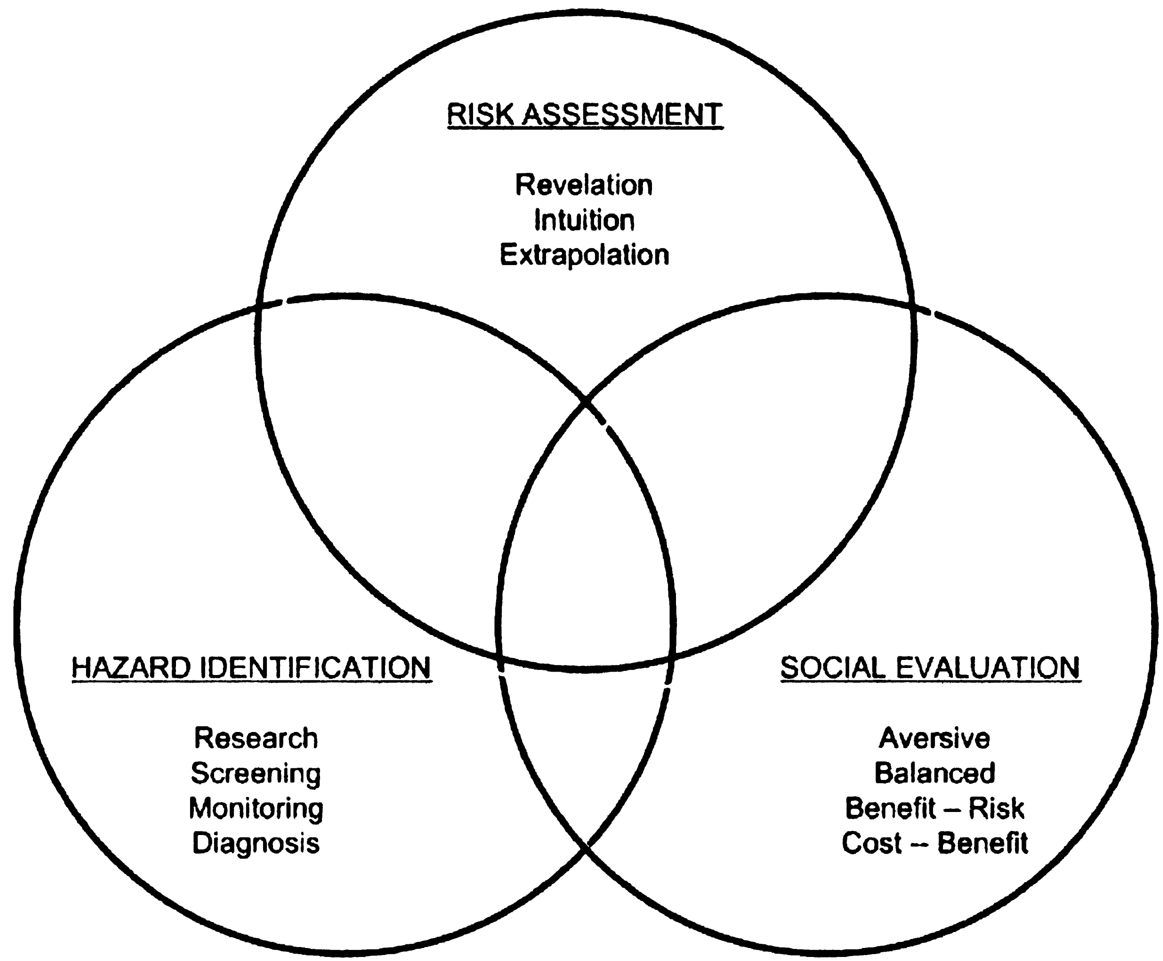

Figure 15. Kates' Model of the Relationship Between the Elements of Risk Assessment (Adapted from Kates, 1978)

In conclusion, this literature review has provided an overview of the overlapping concepts of hazard, risk and disaster. The concepts in the literature review provide a background for understanding the Montserrat disaster. This study will draw on both hazard assessment and risk assessment paradigms to inform the development of the Montserrat Urban and Risk Model.

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CHAPTER 4

SYSTEMS THINKING, SYSTEMS SCIENCE, AND THE SYSTEM DYNAMICS METHOD

4.1 Methods for this Study

The method used for this study is system dynamics. System dynamics is both a perspective and a set of conceptual tools that enables us understand the structure and dynamics of complex systems (Sterman, 2000). As explained in this chapter, the word system itself has been applied as both a metaphor and a method. System dynamics can have many meanings depending on the context, but in this study a specific type of system dynamics will be applied, the system dynamics modeling concept as developed by the work of Jay W. Forrester[30].

This chapter will first comment on the abstract basis of systems modeling as explained by systems thinking and important concept of feedback as it related to system thinking. Systems science will then be described as it is the implementation of the systems thinking concepts. The hard systems as they relate to scientific activity and the soft systems as they relate to addressing ill-structured problems will then be highlighted. The primary method used in this study is system dynamics modeling, based on the work of Forrester. A specific portion of system enquiry called system dynamics will be described and the key modeling developments of industrial dynamics, urban dynamics, and world models will be described. Next, some background material will be provided for interpreting the system dynamics model by describing key elements of the models. Specifically, the concept of the dynamic hypothesis, system boundaries, state variables,

[30] Jay W. Forrester, an engineer and computer scientists at the Massachusetts Institute of Technology, is known as the father of system dynamics.

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feedback loops, stock and flow diagramming notation will be described. To conclude this chapter, a "Simple Montserrat Population Scenario: 2005-2055" system dynamic model will be described, translated into a Powersim computer-based model, and the model will be simulated under conditions based on Montserrat data. This application of the modeling method serves to describe in detail the actual system dynamic modeling process, so that subsequent chapters can focus more on the model itself.

4.2 Systems Thinking

The essences of the systems thinking are the concepts are holism and interconnectedness. Systems thinking operates from the principle that structure influences behavior. Systems thinking is practiced through simulation. Figure 16 depicts how Senge has illustrated the basic concepts of systems thinking with the use a pyramid diagram (Senge, 1990). From a systems thinking perspective, the world is viewed as a complex system where everything is connected to everything else. If people adopt such a holistic worldview, it has been argued that they would act in consonance with the long-term best interests of the system as a whole, identify the high leverage points in systems, and avoid policy resistance (Sterman, 2000).

A basic core idea of systems thinking is that a complex whole may have properties which refer to the whole but are meaningless in terms of the parts which make up the whole. These are the so-called 'emergent' properties. For example, the vehicular potential of a bicycle is an emergent property of the combined parts of a bicycle when they are assembled in a particular way to make a structured whole (Checkland & Scholes, 1990).

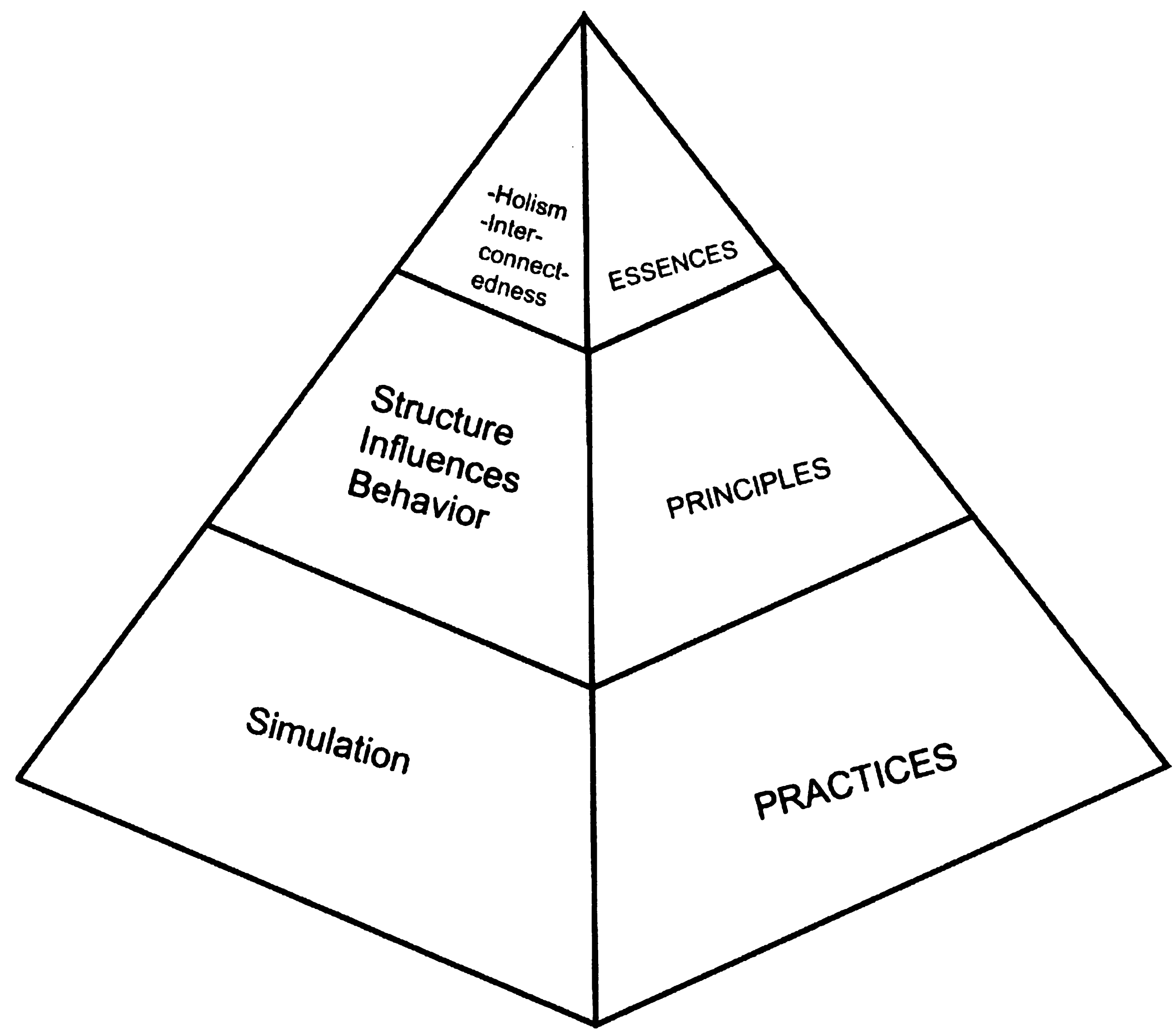


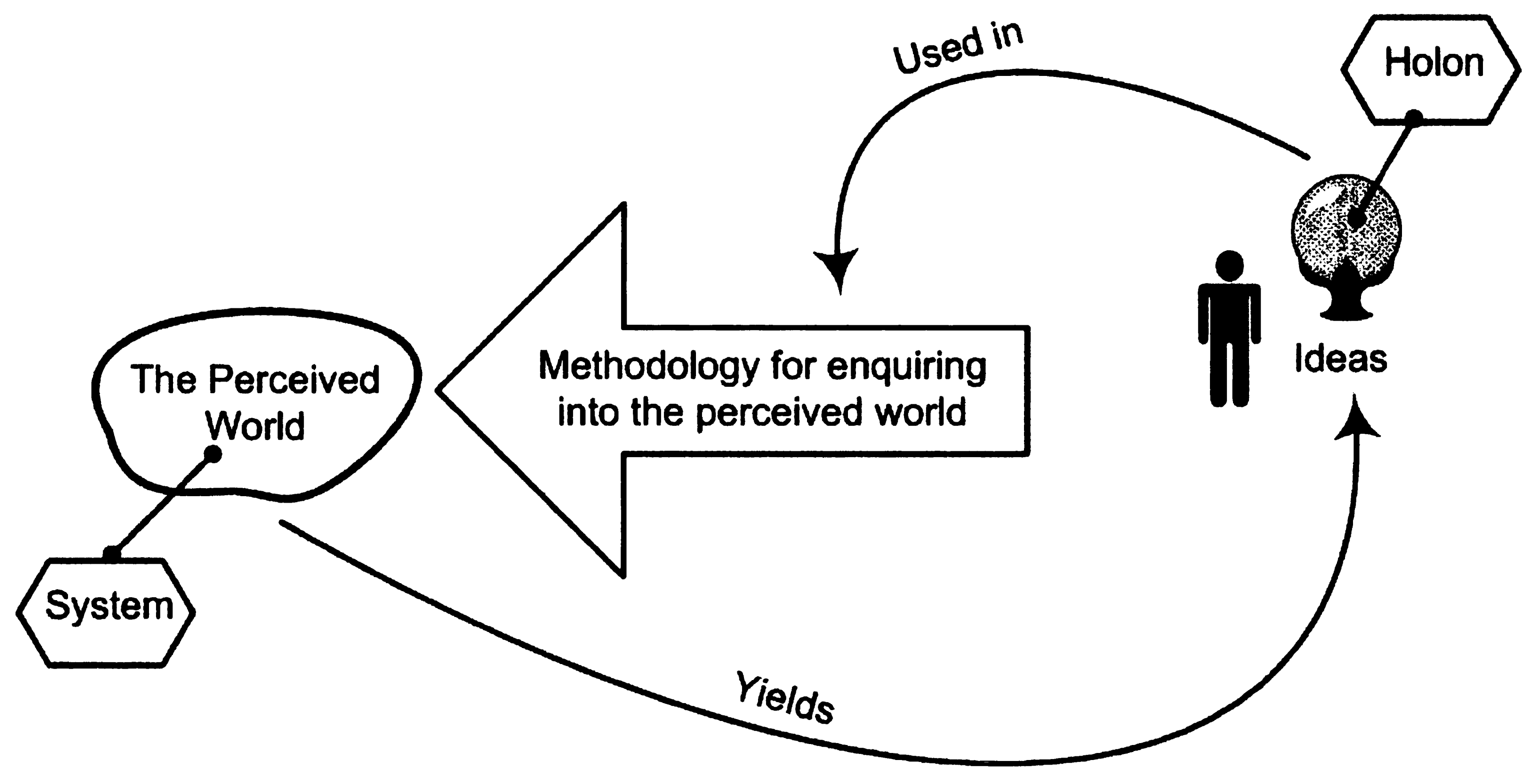
Figure 16. Levels of Systems Thinking (Adapted from Senge, 1990)

The concept of emergent properties implies a view of reality as existing in layers of a hierarchy. In biology, from atoms to molecules to cells to organs to organisms, an observer can describe emergent properties which define the existence of a layer. In addition to the hierarchically organized whole having emergent properties, Checkland comments that a system may be able to survive in a changing environment if it has processes of communication and control which enable it to adapt in response to shocks from the environment. Using these concepts, according to Checkland a system can be defined as a cluster of two pairs of ideas: emergence and hierarchy; and communication and control. From these ideas, an image of a metaphor of system can de described as the adaptive whole that may be able to survive in a changing environment. To make mental use of that model is to do systems thinking (Checkland & Scholes, 1990).

It is important to note, that to treat something as a system is very different from declaring it to be system. Choosing to think about the world as if it were a system can be helpful, but it is different from arguing that the world is a system, a position which pretends to have knowledge no human can have (Checkland & Scholes, 1990). Such discussions highlight the issue that the word 'system' may not be the best word to describe the abstract concept of the whole.

To remedy that problem, alternatives to the word 'system' have been suggested, such as the word 'holon' (Koestler, 1968). Using this concept, system thinkers are then persons who formulate some holons relevant to aspects of a perceived reality in which they are interested in, and then use the holons in a methodology to find out about, gain insight, or engineer some aspect of the world outside of themselves (Checkland & Scholes, 1990). In addition, Checkland suggests that the use of the holon concept allows for an important clarification between the two complementary schools of thought in systems thinking – the hard and soft systems. Hard systems engineers tackle rather well defined problems while soft systems methodologists address messy, ill-structured, problem situations (Checkland & Scholes, 1990). However, the fundamental difference between the complementary schools of thought is that hard systems thinking assumes that the world contains holons and soft systems thinking takes the stance that the process of enquiry (or methodology itself) can be created as a holon. Therefore, soft systems methodology is systemic in two senses -- it is a systemic process of enquiry, one which happens to make use of systems models (Checkland & Scholes, 1990).

It is important to make a distinction between between the terms 'systematic' and 'systemic'. When most people are asked to form an adjective from the noun system they would likely offer the word 'systematic'. But in referring to the system enquiry the adjective 'systemic' is a more apt description (Checkland & Scholes, 1990). While a more commonly used definition of systemic is related to medical terminology meaning applying to the body as a whole, the better definition to be used in this case is 'concerning the system as a whole'. While this study applies the use of a systems model, a systematic approach does not necessarily have to be based on a use of a systems model. Figure 17 graphically illustrates this concept as the perceived world can be systemic (concerning the system as a whole), the methodologies for enquiring into the world can be systematic. In cases where the perceived world is unknown, the method can be systemic (concerning the system as whole). The latter is typical of soft systems methodologies where ill-defined problems are addressed. If one would survey most



Hard Systems Engineering	Soft Systems Methodologies
If the perceived world is *systemic*	If the perceived world is ???
The Methodology can be *systematic*	The Methodology can be *systemic*

Figure 17. The Shift in Systemicity between Hard and Soft Systems (Adapted from Checkland & Scholes, 1990)

applications of systems modeling, most models usually do not incorporate a systemic dimension or dynamic.

4.2.1 Systems Thinking and Feedback

A key concept of system dynamics related to systems thinking is feedback. Feedback loops have a direct relationship to learning and systems thinking. Just as dynamics relies on feedback, so does learning. Argyris distinguished between two types of learning named single- and double-loop learning (Argyris *et al.*, 1985). This section will describe those types of systems thinking as it is relevant to understanding the application of feedback loops.

In *Industrial Dynamics*, Forrester asserted that all decisions, including learning, take place in the context of feedback loops (Forrester, 1961). Figure 18 depicts represents the most basic type of learning as a classical negative feedback loop that is common to decision making in the social sciences (Richardson, 1991).

In Figure 18, decision makers compare information about the state of the real world to various goals, perceive discrepancies between the desired and actual states, and then take actions that (they believe) will cause the real world to move towards the desired state. However, that basic feedback loop does not recognize that decisions are also a result of applying decisions rules or policies to information about the world as we perceive it (Sterman, 2000).

When mental models of the world are incorporated into a decision making process, single-loop learning takes place. In single loop-learning, information feedback is interpreted by our existing mental models (see Figure 19).

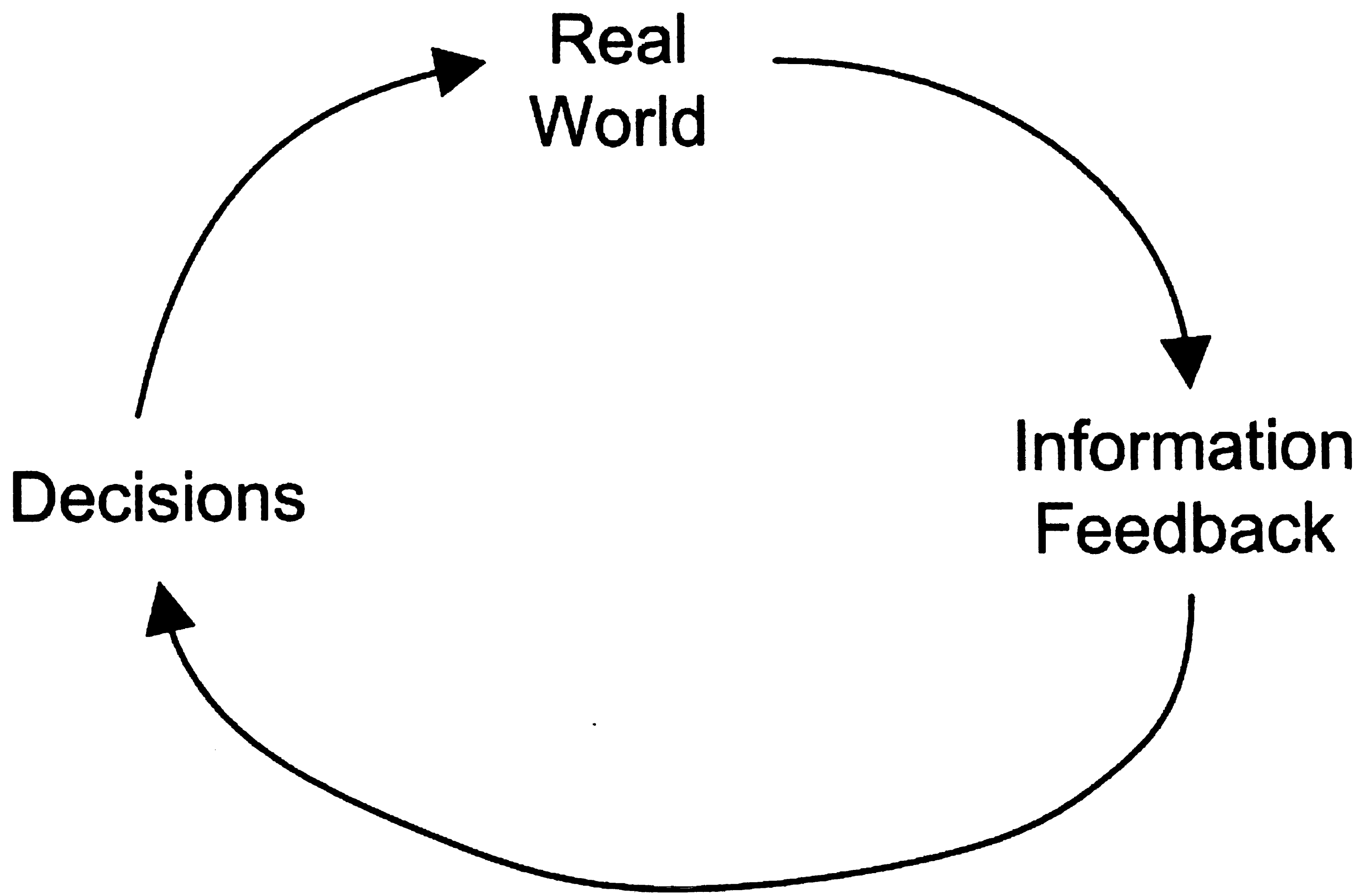


Figure 18. Learning as a Feedback Process (Adapted From Richardson, 1991)

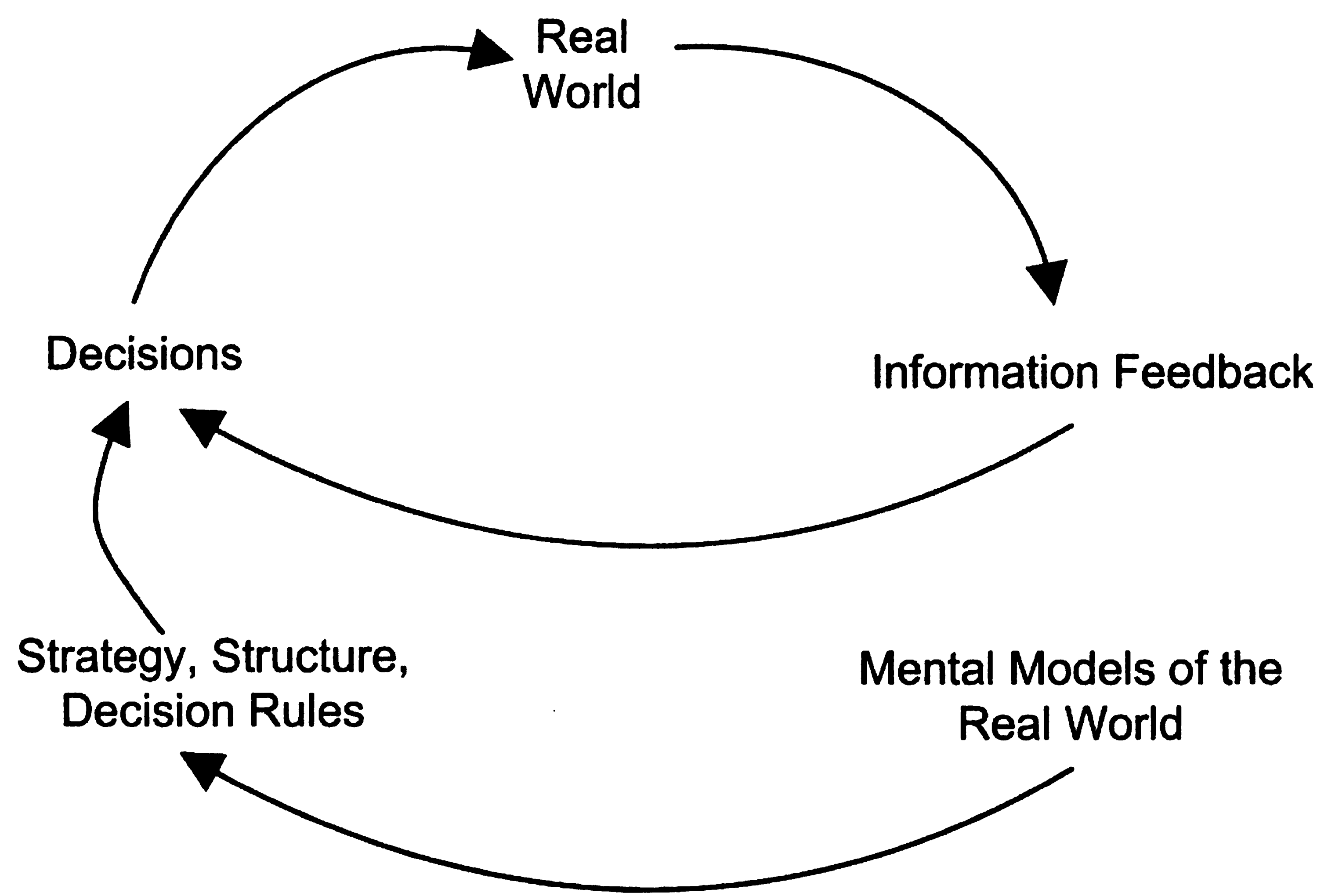


Figure 19. Single-Loop Learning (Adapted From Sterman, 2000)

In terms of systems thinking, single-loop learning is a process by which we reach our current goals in the context of our existing mental models. This type of learning does not result in deep changes to our existing mental models. In other words, our understanding of the causal structure of the system, the boundary which we draw around the system, the time horizon we consider, and relevant and the goals and values do not change (Sterman, 2000).

To advance our fundamental understanding the dynamics of systems, a systems thinking approach suggests double-loop learning (See Figure 20). Double-loop learning is different in that feedback from the real world not only alters our decisions within the context of existing frames and decisions rules, but also it feeds back into our own mental models.

As the mental models change, we change the structure of our systems creating different rules and strategies. In double-loop learning, altering the structure of the decision then alters patterns of behavior. The development of systems thinking is a double-loop process in which we replace a reductionist, narrow, short-term, static view of the world with a holistic, broad, longer-term dynamic view (Sterman, 2000). When double-loop learning is applied to situations, the result can be redesign of policies and institutions.

4.3 Systems Science

Systems science is the implementation of systems thinking concepts. Van Gigch and Kramer proposed a taxonomy for systems science (Van Gigch & Kramer, 1981). It was based on whether systems are taken as ontological (based on being in existence) or

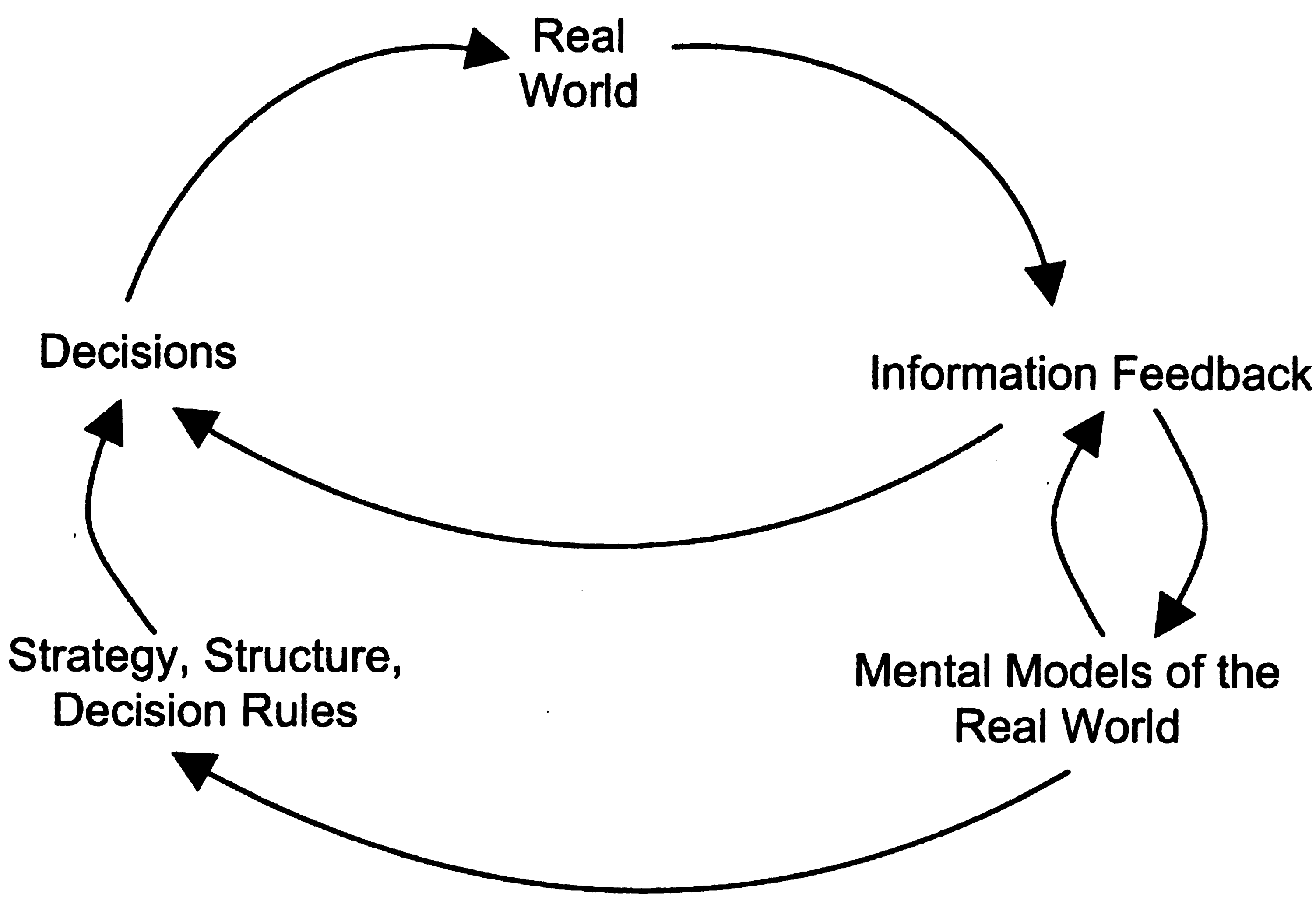


Figure 20. Double-Loop Learning (Adapted From Sterman, 2000)

conceptual, and whether the work done with the systems is theoretical or applied. The four-part matrix that describes the taxonomy of systems science is provided in Table 3.

Checkland (1993) argues that in any subject area the ultimate concern lies in interactions between our lived experience of the world and our conceptual representation of it. In his argument, systems philosophy, axiomatic (or self-evident) systems science, and living systems theory all work towards the purposes of developing systems methodology. The focus on the interactions between theory and practice in systems methodology creates a never ending learning cycle (Checkland, 1984).

One way to look at systems as a subject is to view it as a reaction against the extreme reductionist position (Checkland, 1993). The fundamental ideas of systems science have been developed in many fields, making systems science itself a meta-discipline. Concepts of systems science have been applied to disciplines ranging from engineering to ecology, from anthropology to management.

Within systems science, two fundamental complementary stances have emerged, the positivistic and the phenomenological (Checkland, 1981). The first treats the world as a complex set of systems which could be engineered to achieve objectives. This approach supports the positivistic view taken by experimentalists in the natural sciences. The second views the world as problematic, but assumes that the process of enquiring into it can be systematic. This shift of systemicity from the world to the process of enquiring into it marks the emergence of thinking that parallels the phenomenological stand taken in the social sciences. This distinction is indicative of the difference between 'hard' (systemicity in the world) and 'soft' (systemicity in the process of inquiry) systems thinking (Checkland, 1993). Hard systems are the opposite of soft systems and usually

Systems Science Taxonomy Matrix

	Ontological	Conceptual
Theoretical	Systems Philosophy	Axiomatic Systems Science
Applied	Living Systems Theory	Systems Methodology

Table 3. Taxonomy of Systems Science (Adapted From Van Gigch and Kramer, 1981)

occupy the realm of the physical sciences. Van Gigch cited the following quotation from Checkland and Davies to describe the differences between the hard and soft system approaches:

> "... an inquiring system, a methodology for coping with the messy, ill-structured situations which defeat the "Hard" system approaches (such as system engineering, RAND system analysis, and textbook operations research) which are based upon a goal-seeking model of human behavior and the idea of engineering systems to meet explicit objectives. Soft systems methodology is a general case of systemic inquiry .... Soft systems methodology is doubly systemic. It is itself a cyclic learning system, and within that system's process it makes use of the systems models. The latter are models of purposeful human activities systems, each modeled from the point of view of explicit Weltanschauung [31]...(Van Gigch, 1991)"

This distinction allows us to place hard and soft systems in a context of the systems science in terms of the specialized sciences. This relationship of soft and hard sciences is further elaborated in Figure 21.

4.3.1 Hard Systems

The procedures that characterize science are generally referred to as tools, techniques and methods. A tool is a physical or conceptual instrument that is used in scientific inquiry. Techniques are referred to as a way of accomplishing a scientific objective, or a scientific course of action. Therefore, techniques are ways of using scientific tools. The scientific method is the way techniques are selected in science; that is to the evaluation of alternative courses of scientific action (Ackoff, 1962). This method is applied to studying systemicity in the world, also known as the hard systems. The purpose of the scientific method is to propose a hypothesis and then devise a repeatable experiment in which that hypothesis can be tested. A systems model of scientific activity is represented in Figure 22. The scientific method is an approach of the

[31] Weltanschauung, or worldview, refers to defining the problem in terms of a human-activity system and the observer's perspective.

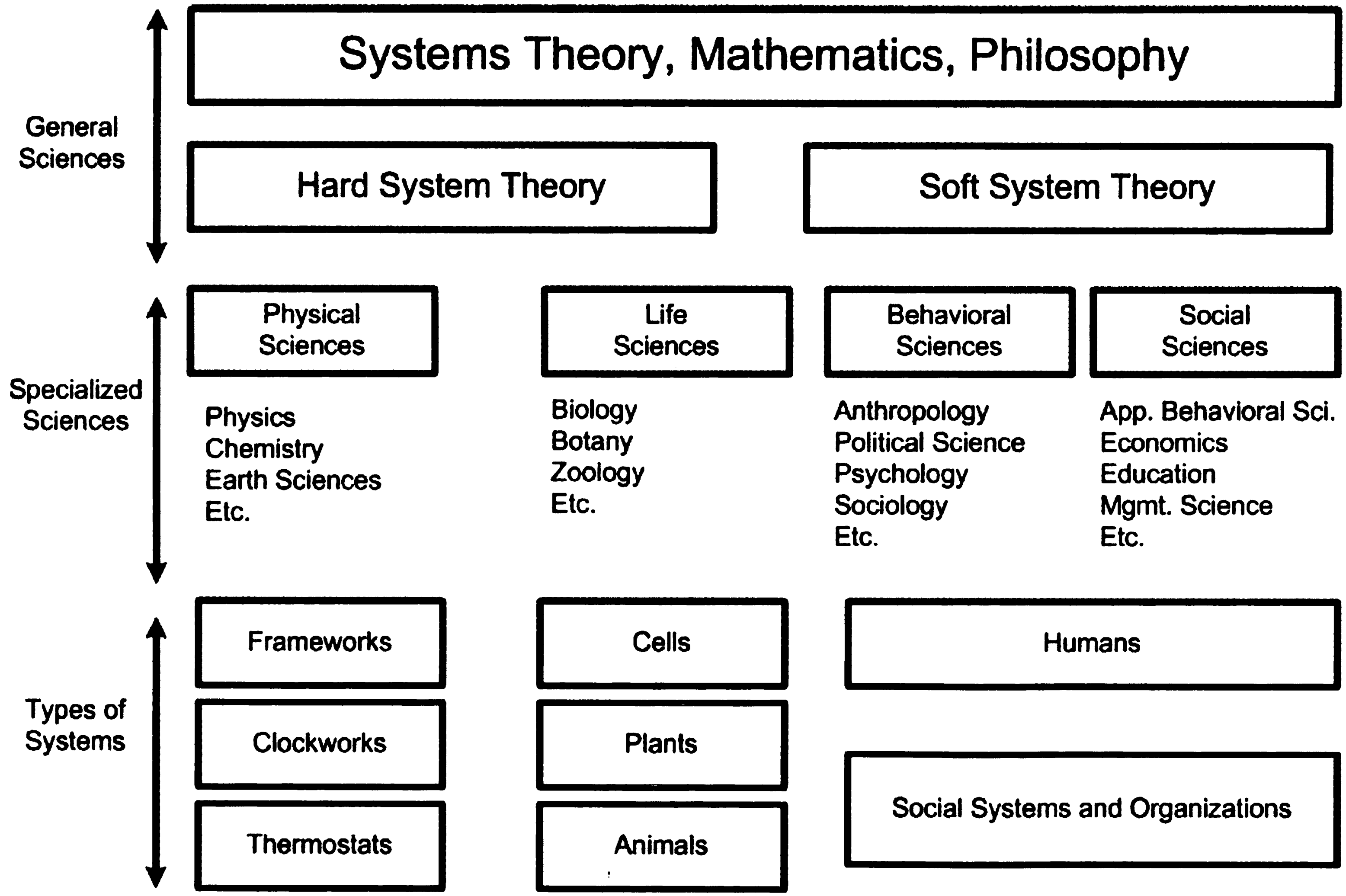


Figure 21. Context of Hard & Soft Systems in Systems Science
(Adapted From Van Gigch, 1991)

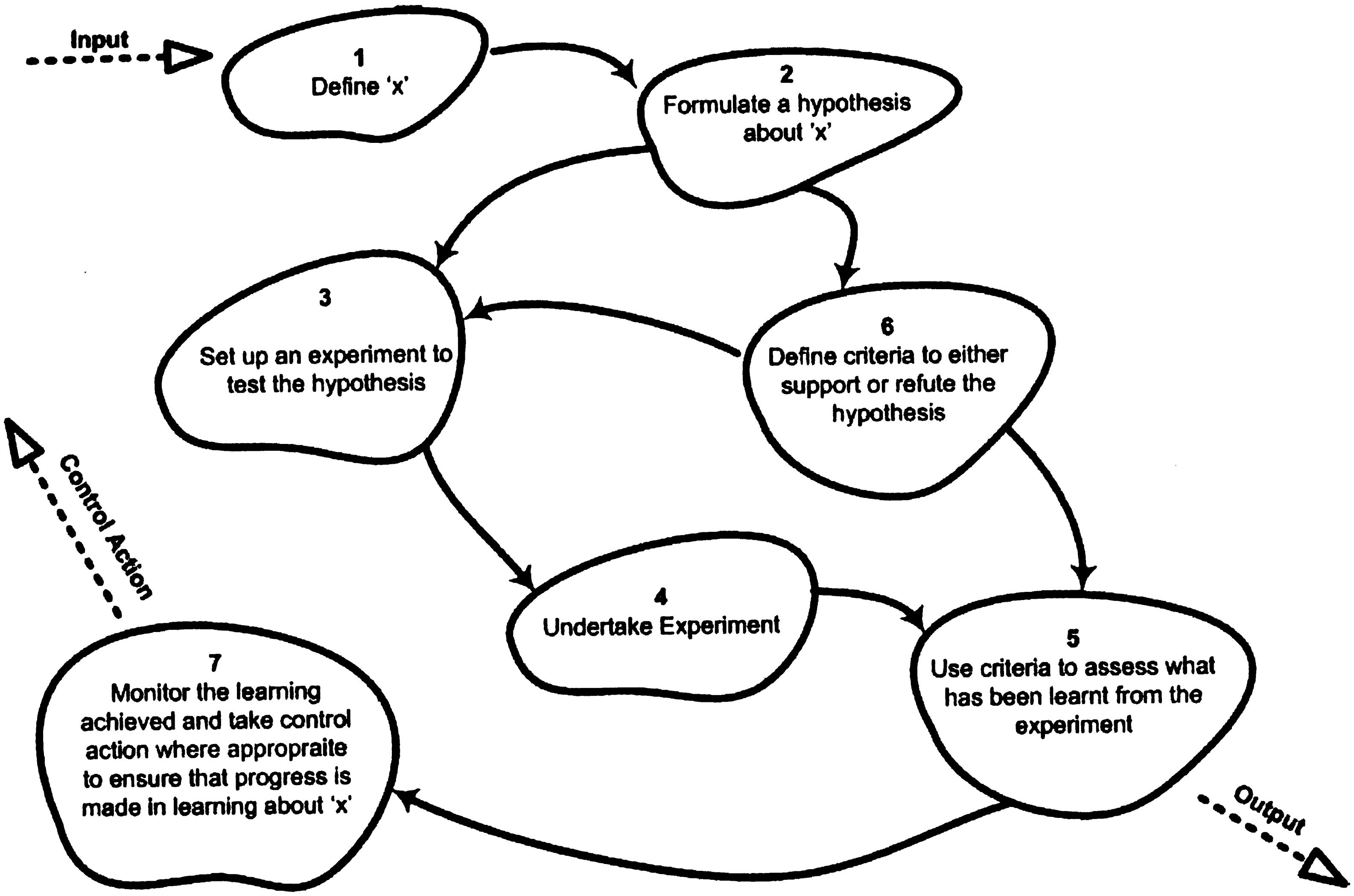


Figure 22. Model of Scientific Activity (Adapted From Wilson, 1984)

physical and related sciences by which hypotheses are postulated, validated and generalized into laws.

The scientific method must be modified to accommodate the special needs of the social sciences. The modification of the scientific method is described as the systems paradigm or as an on-going dynamic, cybernetic, fluid process that describes the approach taken by system designers to formulate plans and strategies for soft systems domains (Wilson, 1990).

4.3.2 Soft Systems

Checkland developed a methodology that is illustrative of soft systems (Wilson, 1990). It represents a paradigm shift from the systems engineering methodologies that are based upon paradigm optimization and interprets the systems paradigm to be one finding out about the real world and taking action (see Figure 23).

The shift has been necessary, given increasing concern about ill-structured, 'soft problems' where there are no such things as right or optimized answers. Therefore, soft systems are defined as having structures that react to their environment by changing their short-term function, undergoing slow long-term changes, but maintaining their identity to evolve. As such, soft systems belong to the social science domain (Wilson, 1990).

4.4 System Dynamics based on Forrester's Work

Within the context of systems science and systems thinking, for the method in this study a very specific aspect of systems science is applied, *system dynamics*. The term system dynamics has varied applications ranging from economics to engineering to management as the following definitions imply. Jay W. Forrester defined system dynamics as:

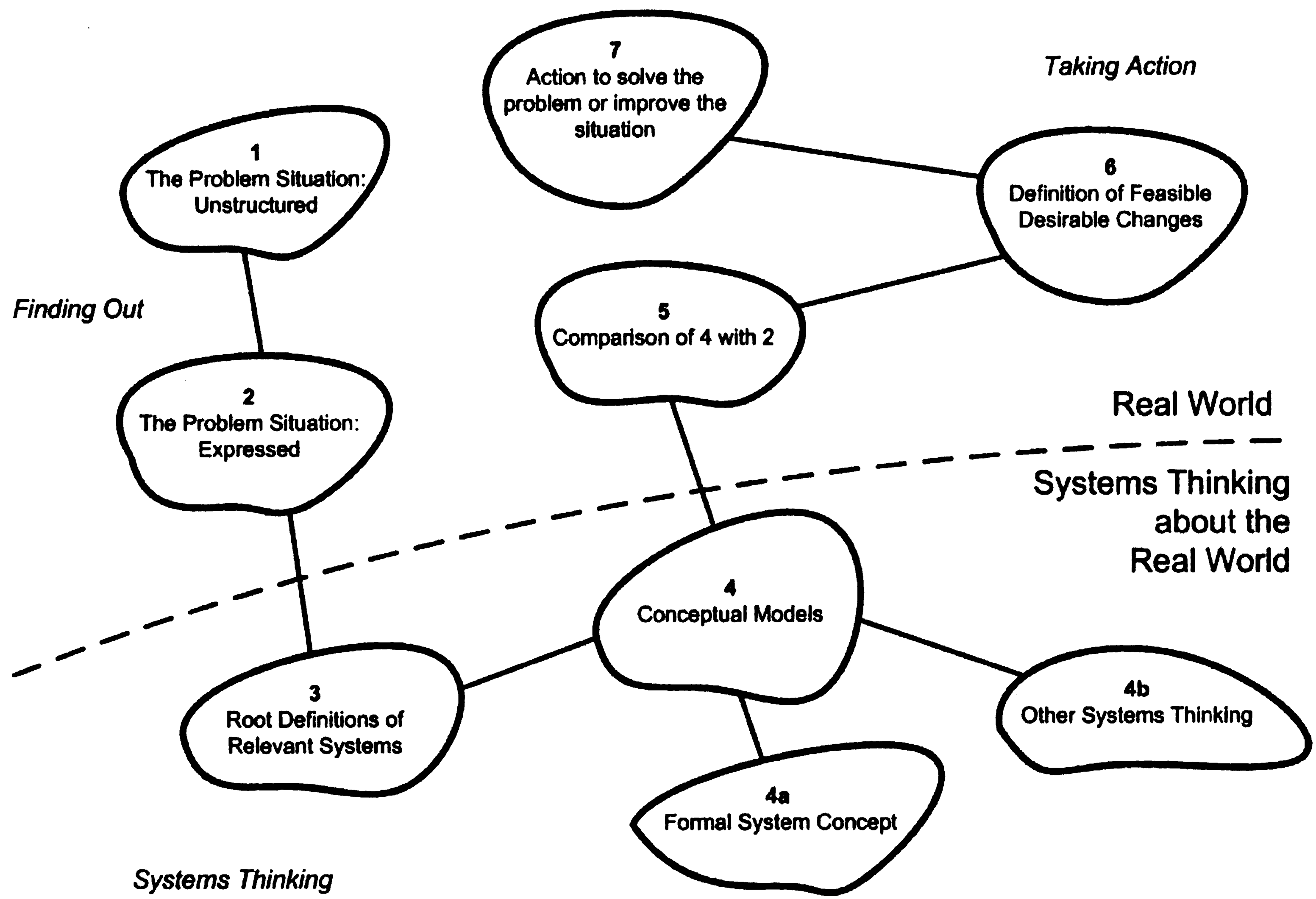


Figure 23. Checkland's Soft Systems Methodology (Adapted From Wilson, 1990)

> "The investigation of the information-feedback characteristics of (managed) systems and the use of models for the design of improved organizational form and guiding policy (Forrester, 1961)."

As defined by Coyle, system dynamics is

> "A method of analyzing problems in which time is an important factor, and which involve the study of how the system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world (Coyle, 1977)."

In an alternative definition suggested by Wolstenholme system dynamics is:

> "A rigorous method for qualitative description, exploration, and analysis of complex systems in terms of their processes, information, organizational boundaries, and strategies; which facilitates quantitative simulation modeling and analysis for the design of system structure and behavior (Wolstenholme, 1990)."

All three of these similar definitions are relevant to this study as information-feedback characteristics of a system will be investigated, time is an important factor, and quantitative simulation modeling will be applied for the design and analysis of systems behavior. The type of system dynamics being applied in this study is based on Forrester's conception of system dynamics and the associated computer modeling methods.

System dynamics models are most effectively used for the general purposes of broad policy making and design for aggregate systems (Meadows & Robinson, 1985). The models are comparatively simple to understand and contain only top-level details of systems being simulated.

It is asserted that in system dynamics modeling, problems can be expressed in terms of time trends or dynamic behaviors patterns. In exploring a new problem, these models look at feedback loops, stocks, flows, material, and information. It is expected

that elements within the systems will respond to each other in a non-linear fashion with time delays.

4.5 The Origin of System Dynamics in Industrial Dynamics

Systems dynamics was developed primarily by Forrester during the late-1950s, as he brought together ideas from the fields of control engineering (the concepts of feedback and system self-regulation), cybernetics (the nature of information and its role in control systems), and organizational theory (the structure of human organizations and the mechanisms of decision-making). From these basic ideas, Forrester developed a guiding philosophy and a set of representational techniques for simulating complex, non-linear, multi-loop feedback systems (Meadows & Robinson, 1985).

One of Forrester's first applications of system dynamics was directed towards the management of industrial firms. Industrial dynamics is the study of the information feedback characteristics of industrial activity to show how organizational structure, amplification in policy, and time delays (in decisions and actions) interact to influence to success of the enterprise. It treats the interactions between the flows of information, material, personnel, and capitol equipment in a company, an industry or a national economy (Forrester, 1961).

The industrial dynamics approach to a social systems organized growth and goal-seeking processes of a system into a computer model. A digital computer was then used to simulate the behavior of the system. The computer simulation revealed the dynamic characteristics of the system that were described in the structure-formulating state. By changing the guiding policy within the system, one can see how the behavior of the actual system might be modified (Forrester, 1969).

4.6 System Dynamics and Urban Dynamics

In addition to industrial dynamics, an important early application of system dynamics was urban dynamics. Urban dynamics models are key to this study as they will be used to inform the models on which this study is based.

During the late-1960s, Forrester organized a team at the Massachusetts Institute of Technology to investigate the dynamics of urban areas in and near Boston. Forrester thought that the term industrial dynamics had become too restrictive because the methods of industrial dynamics were applicable in many other fields other than industrial management. According to Forrester's thinking, the concepts of structure and dynamic behavior apply to all systems that change through time. Therefore, such dynamic systems include can include engineering systems, biology, social systems, psychology, ecology, and all those where positive and negative feedback processes manifest themselves in growth and regulatory action.

The urban dynamics models were driven by ideas such as:

> "The pervasive sense of failure and frustration among men concerned with the management of urban affairs points to the likelihood that the inherent behavior of complex systems defies the intuitively obvious solutions of the past" (Forrester, 1969).

Urban dynamics refuted the conventional wisdom that urban problems are caused by factors which are beyond the control of the city such as such as urban-rural migration, dwindling resources, and suburbanization. Computer based modeling revealed that most urban problems arise from interactions of that occur within the cities themselves (Alfeld & Graham, 1976).

Forrester focused attention on the entire life cycle of an urban area and the tendency to turn away from old decaying inner cities, and to focus on new development that eventually might face the same fate. The urban dynamic models portrayed the city as a system of interacting industries, housing, and people. After analyzing the output of his urban models, Forrester made the policy suggestion that cities should adopt demolition policies to remove slum housing to create space for new industries. These actions could then, in theory, permit a renewal leading to improvements in the city's mix of industries and workers in the city's boundaries. These policy suggestions ran counter to urban planners' thinking and critics faulted the model for being imperfect and oversimplified (Ford, 1999). On the other hand, Forrester thought the model was successful since it forced planners to re-examine their intuitive understanding of the system. Forrester argued that:

> "The human mind is not adapted to interpreting how social systems behave. Our social systems belong to the class of multiple-loop nonlinear feedback systems. In the long history of human evolution, it has not been necessary for man to understand these systems until very recent times. Evolutionary processes have not given us the mental skill needed to interpret properly the dynamic behavior of the systems of which we have now become a part" (Forrester, 1969).

In time, the urban dynamics models were found to be useful as the models identified policies that enabled cities to exercise some control over their own future (Alfeld & Graham, 1976).

4.7 System Dynamics and the World Models

One of the most widely known applications of system dynamics was the world models which were first developed during the late-1960s and early-1970s. The world models are significant in considering global environmental risk and sustainability. In the Resource Development Doctoral Program's coursework, the world models were referenced on numerous occasions in the context of sustainability issues and aspects of systems thinking. The context of the world models will be presented in some detail as they are illustrative of how system dynamics models are both applied to environmental problems and how models may be received by various audiences.

In the late-1960, a non-governmental organization, the Club of Rome, decided to sponsor research concerning the 'predicament of mankind'' (Club of Rome., 1974). In general, members of this club shared one conviction: "That the problems confronting mankind today are too complex and interwoven to be overcome with traditional strategies and institutions (Mesaroviâc & Pestel, 1974)."

For tackling this problem, one of the directors of the club suggested a systems dynamics model developed by a colleague at the Massachusetts Institute of Technology (MIT), Jay Forrester. Forrester was invited to present his methods, and after much discussion Forrester and Club of Rome agreed to work out a set of computer models and equations for preliminary series of models that resulted in the book *World Dynamics* (Forrester, 1971). The momentum caused by Forrester's work lead to another team to form at MIT, directed by one of Forester's former students, Dennis Meadows. This group built on Forrester's model to develop a more comprehensive global model. This effort received a $250,000 grant from the Volkswagon Foundation and as a result *Limits to Growth* was published in 1972 (Meadows & Club of Rome., 1972).

From the 1972 Limits to Growth study, the basic findings concerning natural resources, pollution, population, and quality of life were (Meadows & Club of Rome., 1972):

1. If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

2. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential.

3. If the world's people decide to strive for this second outcome rather than the first, the sooner they begin working to attain it, the greater will be their chances of success.

These world models had many critics. To some critics, *Limits to Growth* was considered as a modern-day version of the views of Thomas Malthus.[32] One viewpoint that critics held was:

> "That mysterious Club of Rome as if it were some kind of international conspiracy of some big-time capitalist-imperialists plutocrats who, warning of big catastrophes if the study growth of population continues and if the production and consumption of irreplaceable material does not come to a standstill within thirty to sixty years, intend to stop the development of the Third World and to maintain their own economic and political hegemony over those regions of the world" (Neurath, 1994).

The point has often been misunderstood that the authors of *Limits to Growth* offered a warning, *not a prediction,* of things that would happen if mankind were to continue to grow its own numbers and if per-capita consumption continued at the rate which it had been and was growing in the early 1970s.

The *Limits to Growth* modelers predicted by middle of the 21st century, that an overshoot and collapse scenario would take place. Overshoot and collapse means to go

[32] Malthus was a British professor of history and political economy in the College of the East India Company who postulated (in the 1820-30s) that since increases in food supply cannot keep pace with geometric increases in human population there would be a time of famine with a stabilization of the human population.

beyond a target or the sustainable carrying capacity of the environment. Overshoot is caused by delays or faults in feedback information that do not allow a system to control itself relative to its limits (Meadows & Club of Rome., 1972). In the 1990's, the Limits to Growth model was revisited. Meadows, Meadows, and Rander (1992) commented that the main conclusions were still valid but needed to be refined.

The world models illustrated both the wide ranging implications and controversy that can be generated by the use of system dynamics modeling methods. These world models developed approximately thirty-five years ago are still relevant to today's global environmental situation. An unique aspect of the Club of Rome studies and *Limits to Growth* reports was that they summarized a highly complex system in a model presented in a way that emphasized the systems themselves, not the intricacies of the equations or the model.

4.8 Elements of the System Dynamics Modeling Method

Before introducing the actual system dynamics modeling process, the following sections will highlight selected elements of system dynamics in order to provide a background necessary for interpreting the models. Both a characterization of a generalized system dynamics model and a description of the dynamic hypothesis concept will be provided, as they explain the reasons that models are constructed. A discussion of system boundaries follows as the boundaries are an important descriptive element of a system dynamics model. Then, the two key elements of a system dynamics model will be described – feedback loops and state variables. Finally, before depicting a population dynamics model, the stock and flow diagramming notation will be illustrated with the use of the hydraulic metaphor for system dynamics modeling.

4.8.1 Characteristics of System Dynamics Models

System dynamics model are most effectively used for the general purposes of broad policy making and design for aggregate systems (Meadows & Robinson, 1985). The models are comparatively simple to understand and contain only top-level details of systems being simulated. Also, the underlying assumptions are explicitly detailed.

It is asserted that in system dynamics modeling, problems can be expressed in terms of time trends or dynamic behaviors patterns. In exploring a new problem, these models look at feedback loops, stocks, flows, material, and information. It is expected that elements within the system will respond to each other in a non-linear fashion with time delays.

In system dynamics models, it is important to realize that when considering mathematical models, they may only be used to predict certain aspects of the system's response to inputs. Using an engineering example, a mathematical model of an aircraft may be designed to predict how a proposed aircraft would respond to pilot commands, but it would not have the capability of predicting other aspects of real aircraft response such as aerodynamic heating. Due to the abstract nature of system models, they should not be considered as replication of the entire system, but rather a tool for analyzing only specific parts of system (Karnopp *et al.*, 2000).

4.8.1.1 The Dynamic Hypothesis

Once a problem has been identified and characterized, over the appropriate time horizon, a theory is developed called a dynamic hypothesis. The hypothesis is intended to account for the problematic behavior within the system. The dynamic hypothesis characterizes the problem in terms of the underlying feedback and stock and flow structures of the system. It is a hypothesis because it is provisional as it subject to revision or abandonment, as learning from the modeling process itself and real world takes place. In other words, the dynamic hypothesis is a working model of how the problem arose. The goal of the modeling process is to develop an endogenous explanation (rising from within) for the problem's dynamics (Sterman, 2000).

4.8.1.2 System Boundaries

A basic assumption about a system is that it is an entity that can be separated from the universe by a physical or conceptual boundary.

Examples of such system boundaries are an animal's system or an air traffic control system (Karnopp et al., 2000). The boundary of an animal system is its skin. The system reacts to the surrounding environment (air temperature) and it the exchanges energy and information with its environment. An animal's skin is a tangible boundary. An example of a conceptual boundary is found in the air traffic control system – a system that is a complex man-made system that includes the physical surroundings of air traffic, along with the fluctuating demands for air traffic which ultimately come from decisions concerning travel and the movement of goods. Both systems allow for the ability to decide what belongs within the system and what represents an external condition, disturbance, or command from outside of the system. In this study, a model will be developed with a conceptual boundary.

Model boundaries are very important descriptive elements of the system dynamics models. The basic function of a model's boundary diagram is to make explicit what has been included and not included in the model itself. Figure 24 is an illustration of a bulls-eye type diagram that depicts model boundaries.

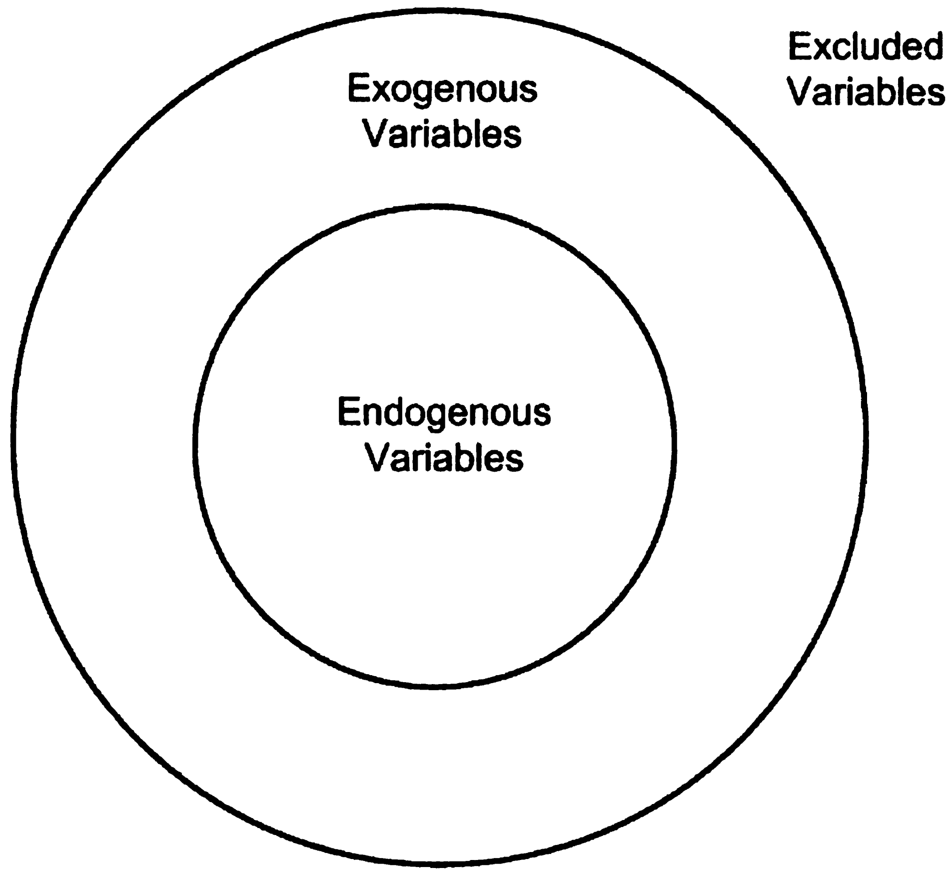


Figure 24. A Bulls-Eye Type Model for Depicting Model Boundaries
(Adapted from Ford, 1999)

The bulls-eye model categorizes three groups of variables, the endogenous, exogenous, and excluded (Meadows & Robinson, 1985). In the bulls-eye diagram, the endogenous variables are in the innermost circle. They are determined or calculated within the model. The endogenous variables are those contained within the feedback loops. The exogenous variables lie within the outermost circle. These variables affect the state of the model, but they are not affected by the model itself. Exogenous variables are either constants of driving functions that must be specified before the model can be run. Those variables listed outside of the circles are omitted or excluded. While this list can be endless, the purpose of the excluded variables is to draw attention to the assumptions made to define the models boundaries and to indicate the potential areas for the model's expansion.

4.8.1.3 State Variables

A systems dynamics model is a state-determined system. In the language of mathematics, the system model is described by a set of ordinary differential equations of *state variables* and a set of algebraic equations that are related to other variables of interest to the state variables. Table 4 illustrates the relationship between characteristics of steady state and dynamic variables.

State-determined systems are extremely useful since the future of all variables associated with a state-determined system can be predicted if: 1) the state variables are known at some initial point in time, and when 2) the future time history of the inputs from the environment is known (Wilson, 1990).

Dynamic and Steady State Model Matrix

	Steady State	Dynamic
Deterministic	Algebraic Equations	Differential Equations
Non-Deterministic	Statistical and Probability Relationships	Discrete Event Simulation

Table 4. Distinctions Between Dynamic & Steady State Models (Adapted From Wilson, 1984)

4.8.1.4 Feedback Loops

All dynamics arise from the interactions of two types of feedback loops, positive and negative feedback loops.

A positive feedback loop is also known as a self-reinforcing loop. Positive loops will tend to amplify whatever is happening in the system. An example of a positive feedback loop is represented by the concept of the vicious circle. While in modern times a vicious circle is commonly referred to as a bad situation that leads to its own worsening, the phase and concept have meaning in formal logic.[33] Richardson (1991) has used an excerpt from nineteenth French literature to illustrate a vicious circle (Richardson, 1991):

> "I'd need rest to refresh my brain, and to get rest it is necessary to travel, and to travel, one must have money, and to get money you have to work, create, etc. I am in a vicious circle (cerle vicieux) from which it is impossible to escape" (Balzac, 1906).

Figure 25 illustrates the positive feedback loop of the vicious circle. The positive feedback loop is an explicitly circular process, perceived as characteristically self-perpetuating and self-reinforcing.

On the other hand, negative feedback loops counteract and oppose change. Negative feedback loops are self-correcting and they reflect processes that seek balance and equilibrium. A simple example of a negative feedback loop adapted from Sterman (2000) is illustrated by the situation of chickens crossing a road (see Figure 26). The more the chicken population grows, the more road crossings they will attempt.

[33] In Victorian times, the word vicious meant among other things, flawed or faulty. Any fallacious argument was known to be faulty or flawed – basing an argument on the very proposition to be proved. Such an argument was known to be a vicious circle, meaning a process of reasoning that is faulty because it is circular (Richardson, 1991).

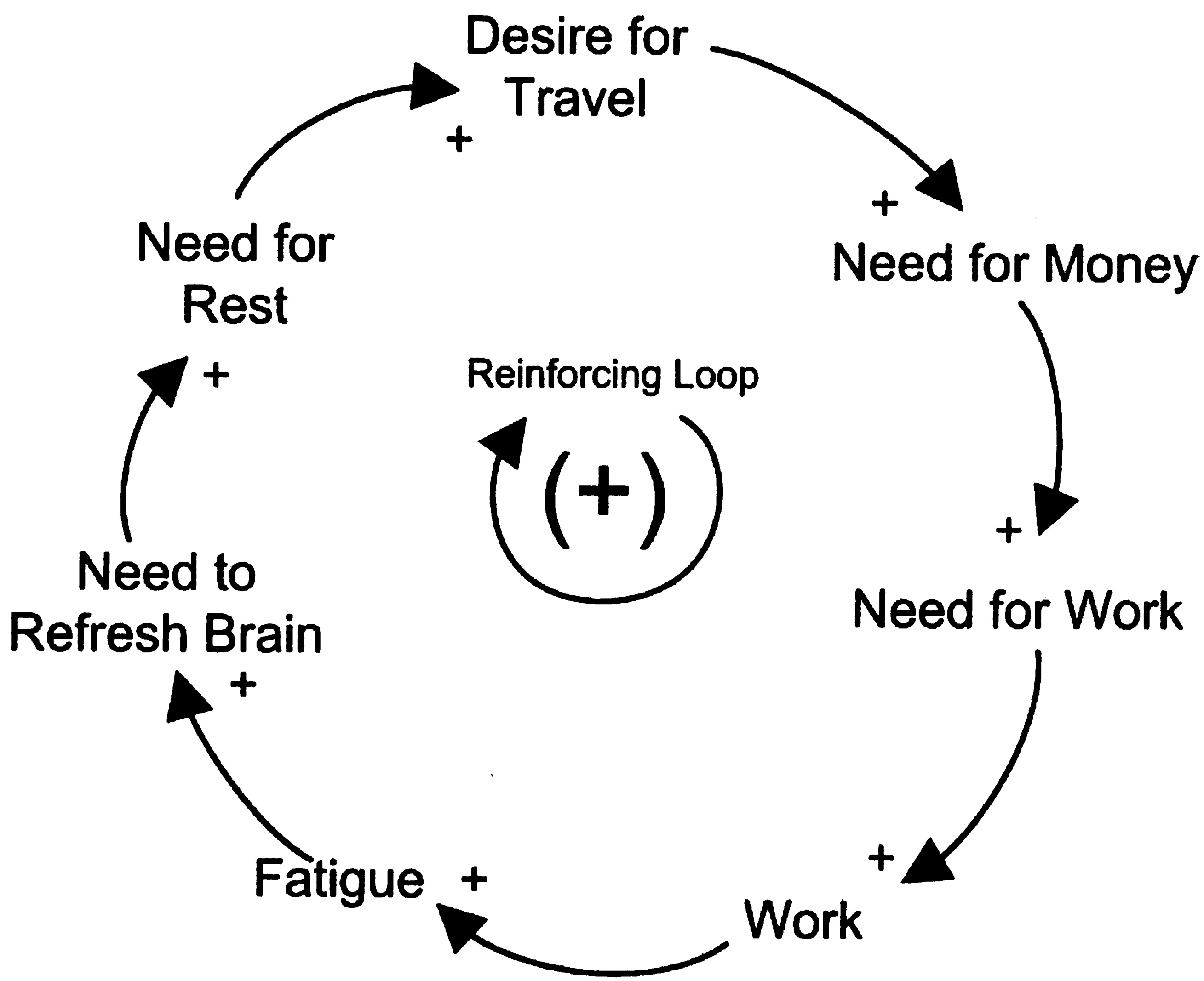


Figure 25. The Vicious Circle Positive Feedback Loop (Adapted From Richardson, 1991)

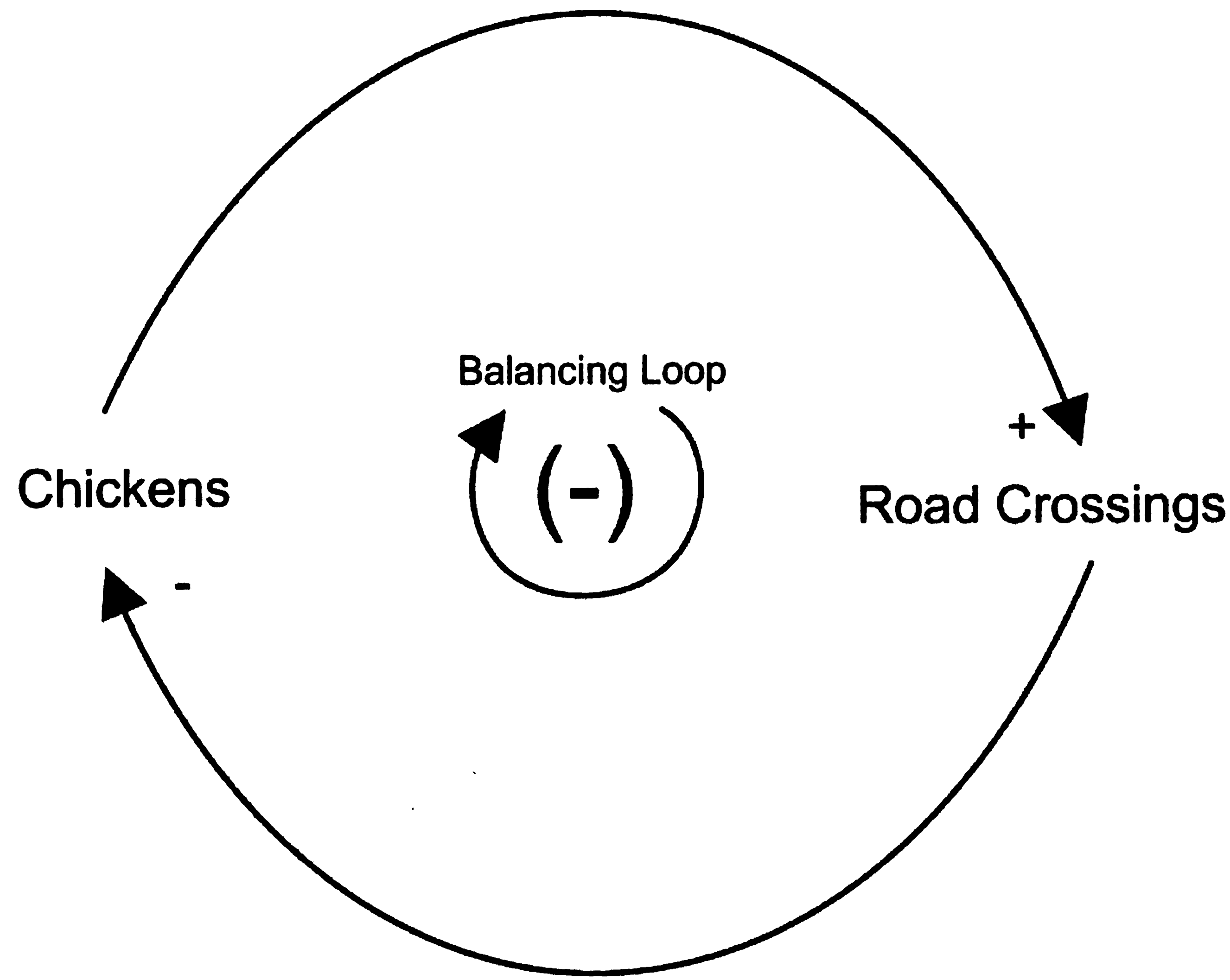


Figure 26. Negative Feedback Loop (Adapted From Sterman, 2000)

Assuming there is traffic and the road crossings are risky, some chickens will not make it to the other side. Therefore, more road crossings will lead to fewer chickens (hence the negative polarity for the link from road crossings to chickens). An increase in the chicken population will lead to more risky road crossings which will result in the chicken population being lowered. Therefore, the negative feedback loop keeps the population in balance.

No matter how complex a system, at its base the system consists of networks of positive and negative feedback loops. All dynamics arise from the interaction of these loops with one another (Sterman, 2000).

4.8.1.5 Stock and Flow Diagramming Notation

Forrester's original concepts of stock and flow diagrams were based on a hydraulic metaphor depicting the flow of water in and out of reservoirs. Figure 27 graphically illustrates the hydraulic metaphor in relation to an equivalent stock and flow diagram.

System dynamics modeling uses a particular diagramming protocol for stocks and flows. The conventions were initially suggested by Forrester in his industrial dynamics work (Forrester, 1961). The primary components of stock and flow diagramming are stocks, inflows, outflows, valves, and clouds, as illustrated in Figure 27.

In the stock and flow diagramming notation, stocks are represented by rectangles suggesting a container holding the contents of the stock. Inflows are represented by a pipe with an arrow pointing into (adding to) the stock. Outflows are represented by pipes pointing out from (subtracting from) the stock. The valves control the flow. Clouds represent the sources and sinks for the flows. Stocks outside the model boundary

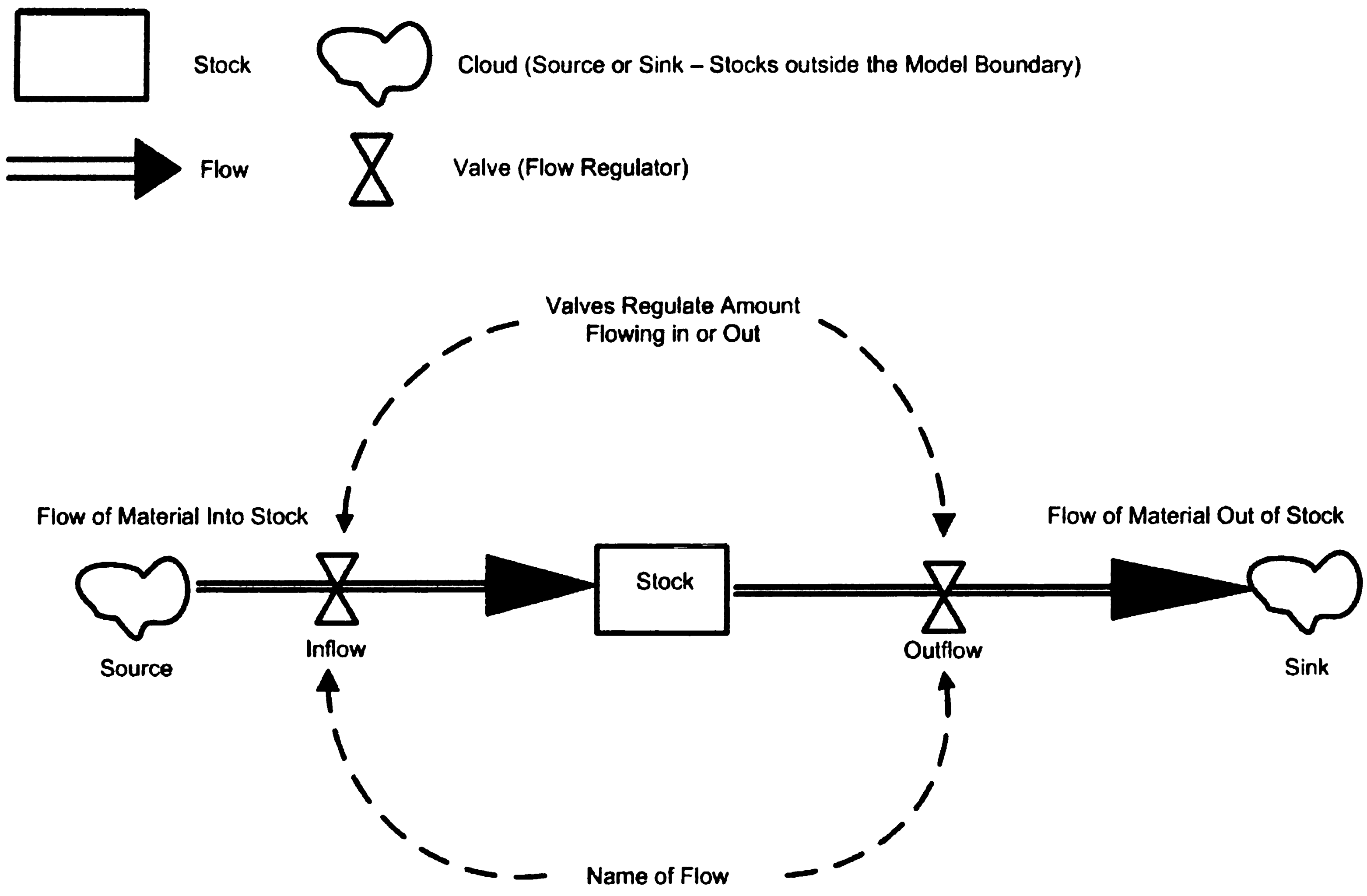


Figure 27. Stock and Flow Diagramming Notation (Adapted From Sterman, 2000)

represent stocks into which flows leaving the model boundary drain. They are assumed to have infinite capacity but they can never constrain the flows they support.

Alternatively, the hydraulic metaphor can also be represented in mathematical terms. Stocks accumulate or integrate their flows: the net flow into the stock is the rate of change of the stock. The hydraulic metaphor and the stock and flow diagram represented in Figure 27 exactly corresponds to the following equation:

$$\text{Stock}(t) = \int_{t_0}^{t} [\text{inflow}(s) - \text{outflow}(s)]ds + \text{Stock } t_0$$

Where inflow(s) represents the value of the inflow at any time s between the time t_0 and the current time t. Equivalently, the net rate of change of any stock, its derivative, is inflow less the outflow, defining the differential equation:

$$d(\text{stock})/dt = \text{Net Change in Stock} = \text{inflow}(t) - \text{outflow}(t)$$

Table 5 illustrates mathematical interpretations underlying causal loop diagrams. In terms of mathematics, stocks integrate their net flows; and the net flow is the derivate of the stock. Causal loop diagrams operate according to the two fundamental principles of calculus: integration and differentiation (Sterman, 2000). One way of interpreting the behavior of the flows over time is by applying the principles of graphical integration. Graphical integration implies if one looks at a graph of the behavior of flows over time, one can always infer the behavior of the stock. Stocks accumulate or integrate their net flow. The slope of any line tangent to any point of the tangent, to any point of the trajectory of the stock, equals the net rate of change for the stock at that point. The slope of the stock trajectory is the derivative of the stock at that point. In this study,

Symbolic Representation	Verbal Interpretation	Mathematic Interpretation
	All else being equal, if x increases (decreases), then y increases (decreases) above (below) what it would have been In the case of accumulations, x adds to y	The slope of the stock trajectory is the derivative of the stock at that point, expressed as the partial differential equation: $\partial Y/\partial x > 0$ In the case of accumulations, it can be expressed as an integration: $Y = \int_{t_0}^{t} (x + \ldots) ds + y_{t_0}$
	All else being equal, if x increases (decreases), then y decreases (increases) above (below) what it would have been In the case of accumulations x subtracts from y	The slope of the stock trajectory is the derivative of the stock at that point expressed as the partial differential equation: $\partial Y/\partial x < 0$ In the case of accumulations, it can be expressed as an integration: $Y = \int_{t_0}^{t} (-x + \ldots) ds + y_{t_0}$

Table 5. Mathematical Interpretations of Link Polarity (Adapted From Sterman, 2000)

system dynamic software will be used where the modeler sets the parameters for the calculus-based calculations.

In general, the flows will be functions of the stock and other state variables. While the integration and differentiation equations may appear more rigorous than the graphic representation of the hydraulic flow metaphor, they are equivalent and represent the same information. In this study, stock and flow diagram nomenclature is applied to describe the dynamic model.

4.9 System Dynamics Population Model Example

To conclude this chapter, a simple system dynamics model will be created, and details will be provided explaining the steps in the modeling process. In the system dynamics modeling method applied for this study, causal loop diagrams will be designed using computer modeling software[34]. While in this section, more detailed explanations and definitions are provided for the model, in subsequent chapters the focus will be more on the model itself, than the methods per se.

The example provided to illustrate the method is a simple system dynamics model based on a theoretical scenario related to future population dynamics for Montserrat. The example is based on the question, if it were possible to seal off Montserrat, with no persons coming onto or leaving the island, what would happen to island's population during the next 50 years?

A systems dynamics model "Simple Montserrat Population Scenario: 2005-2005" will be created as follows:

1. A causal loop diagram will be illustrated for the population dynamics model

[34] The example model in chapter four was developed using the computer software Powersim Studio Academic 2005.

2. The causal loop diagram will be translated to a Powersim-based model
3. Values will be added to the model appropriate to Montserrat
4. The dynamic simulation will be run and conclusions will be drawn

This model was chosen as the example since it is a portion of the larger model applied in subsequent chapters.

4.9.1 Population Model Casual Loop Diagram.

Causal loop diagrams are a technique to portray the information feedback at work in a system. The word *'causal'* refers to cause and effect relationships. The work *'loop'* refers to a closed chain of cause and effect (Ford, 1999). Causal loop diagrams are used to couple positive and negative feedback loops. Such diagrams are important since they allow for quickly capturing the hypothesis about the causes of dynamics (Sterman, 2000).

Figure 28 depicts a causal loop diagram for a dynamic model of population. The variables of both birth and death work through population as a common variable. In this case, population is known as the stock or state variable, where a quantity of people is either added by inflows or subtracted by outflows.

In the diagram, the causal links are represented by arrows. Each arrow is assigned a polarity, depicted by a '+' or '-'sign near the arrowhead. The polarity indicates how the dependent variable changes when the independent variable changes. Also, in the center of the birth and death feedback loops there is a loop identifier indicating whether the loop is reinforcing (positive) or balancing (negative) feedback loop. A positive link means that if the cause increases, the effect increases above what it would haven been otherwise, and conversely if the cause decreases, the effect decreases below what it would have been otherwise. In the population causal loop diagram, an increase in the birth rate means that

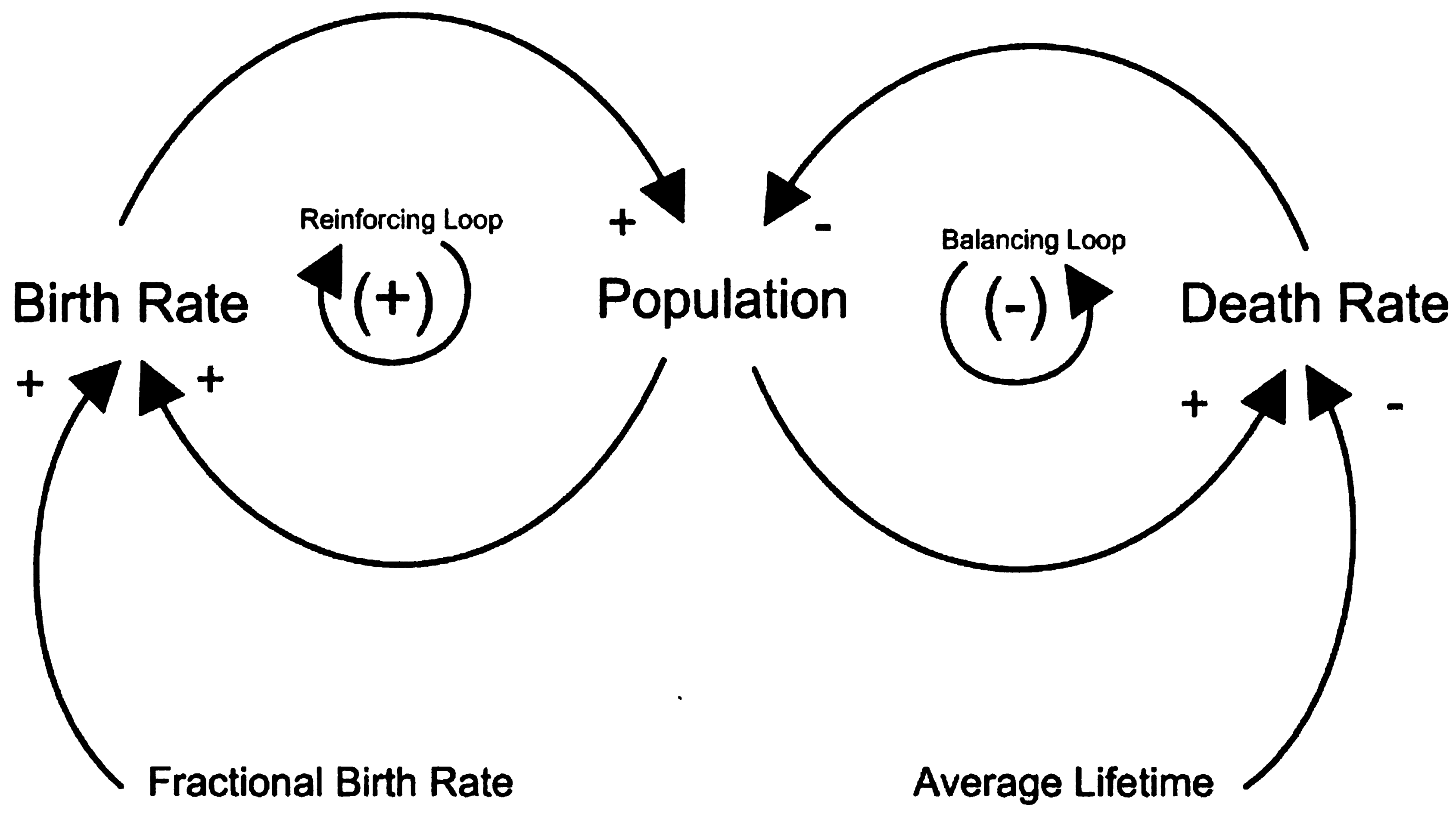


Figure 28. Causal Loop Diagram for Population Dynamics (Adapted From Sterman, 2000)

the birth rate will increase above what it would have been. That is, if the fertility rises, the birth rate, given the population, also will rise. When the cause is a rate of the flow that accumulates into a stock, then it is also true that the cause adds to stock (Sterman, 2000). Link polarities describe the structure of the system. They do not describe the behavior of the variables. In other words they do not describe what actually happens - they describe what would happen *if* there were a change (Sterman, 2000).

4.9.2 Casual Loop Diagram Translated to Powersim Computer Model

Figure 29 represents what the causal loop diagram from Figure 28 looks like when it is translated to a Powersim computer-based model. Figure 29 also provides the legend for the model's symbols along with information relevant to the variables in the model. As system dynamics models use a particular diagramming protocol based on conventions that were initially suggested by Forrester, the Powersim software uses conventions based on adaptations of Forrester's original protocol. Some of the following language was adapted from Powersim's online help screen.

The square is a *state variable* (also called *levels* or *stocks).* These levels accumulate their value over the time of the simulation. The value is changed by the flows, or double arrows running in and out of the level. The level is called a state variable because it represents the state of the system. In the example model, the state variable is named population, it is set at a numerical value, and the unit is people.

The connector with a double line is a *flow.* Flows represent time delays in the system. The time delays are represented by time step changes and the value of the auxiliary controlling the flow, or the flow rate. Flows create feedback structures in the dynamic system.

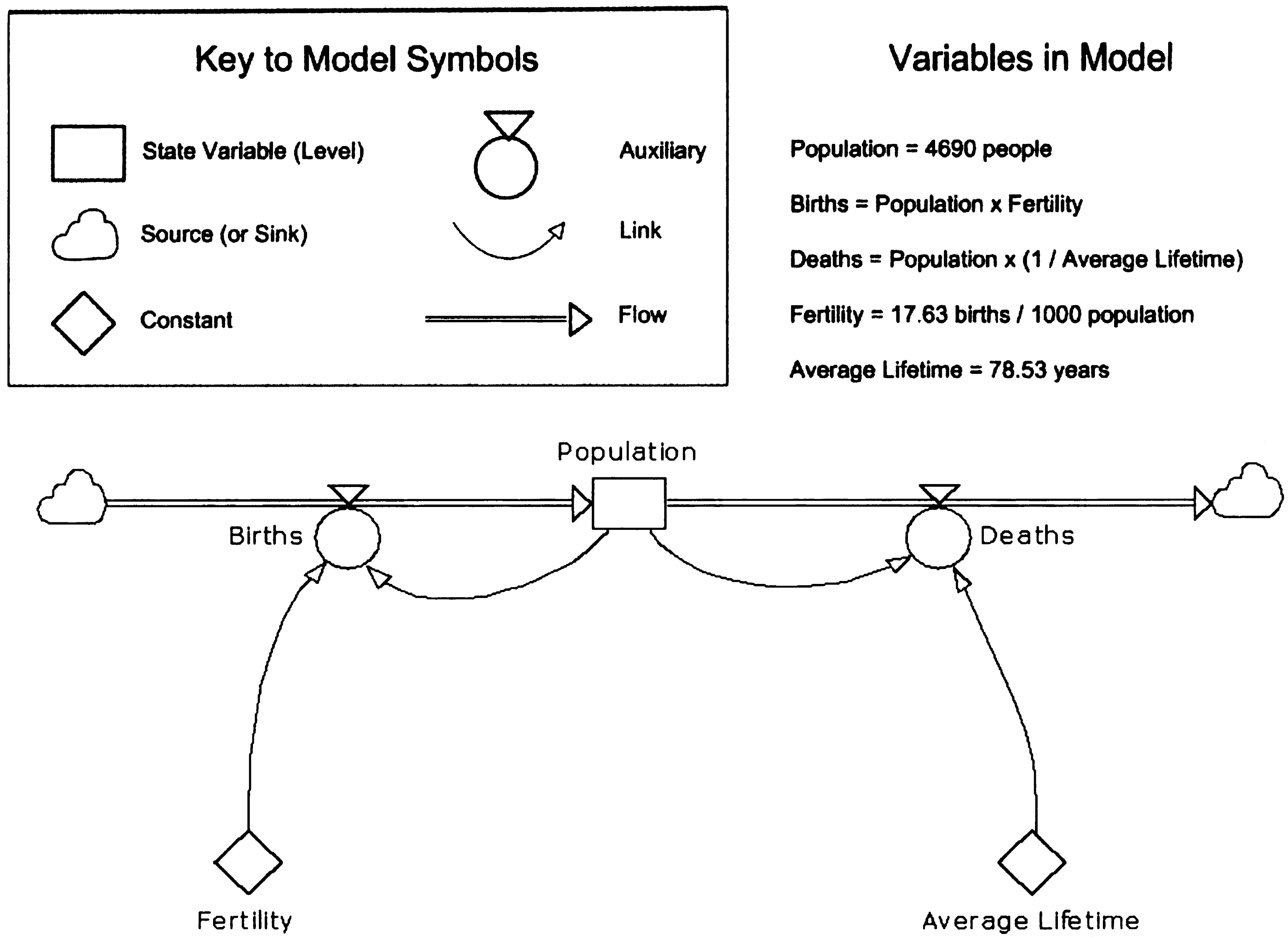


Figure 29. Population Causal Loop Diagram Translated to a Powersim Computer Model

The *clouds* represent a source or a sink. The flows originate from the clouds or end in the clouds. The clouds are stocks outside of the model boundary. They can be either a source or sink for state variables. As the clouds represent elements outside of the model boundary, what happens at the source or sink is not necessarily of concern to the model.

The circle is an *auxiliary* variable. The values of auxiliaries are calculated once every time step. The algebraic calculations used in the auxiliaries can include any combination of levels or other auxiliaries. Auxiliaries have no memory, unlike levels. Flow rates are auxiliaries used to control the flows in and out of levels. In the example model there are two auxiliaries, births and deaths. For births, the auxiliary variable is defined by the equation

Population * Fertility

and the unit is people / year. For deaths, the auxiliary variable is defined by the equation

Population * (1 / Average Lifetime)

and the unit is people / year.

The diamond is a *constant*. These variables remain the same throughout the simulation. Using computer modeling methods, through various controls, constants can be used to provide input to the model. In the example model, there are two constants named fertility and average lifetime. Fertility is defined with a numerical value and the unit is 1 / year. Average lifetime is also defined with a numerical value and the unit is years.

The single lines with arrowheads are *links*. Links are connectors that indicate that the variable at the start of the link is used to define the variable at the end of the link. In the example model, the links indicate that the auxiliary of births is defined by both population and fertility.

4.9.3 Application of the Model to the Montserrat Population Situation

The population model described above will now be applied to the situation of Montserrat. In adapting the models to real life circumstances, values are assigned from some real world situation. In this case, the base 2005 population for Montserrat was given a value of 4,690 persons[35]. Data for fertility rate and average lifespan for Montserrat was drawn U.S. Central Intelligence Agency data (United States Central Intelligence Agency, 2005). According to those data for Montserrat, year 2004 estimates place the birth rate on the island at 17.63 births / 1,000 population and the life expectancy at birth is 78.53 years.

In the example model, the assumption is made that the growth or decline population over time will be influenced only by the factors of fertility and the average lifespan. Clearly, in a real life, many other influences such as in-migration on out-migration will effect population on the island, but for the purposes of this example only two factors will be considered. As with any system dynamics modeling, assumptions must be made as to what to include and not include in the model. In the modeling process, the modeler makes the decision as to what variables are used and provides an explanation as to why such choices were made.

4.9.4 Population Model Simulations and Conclusions

Once all the parameters have been established, the model can be run under the simulated conditions. The scenario that will be modeled will be population dynamics on

[35] See Chapter 2, for information concerning Montserrat's population.

the island for the next 50 years. In modeling, a decision is made by the modeler to determine appropriate temporal aspects for the model.

In the case of this model, the variable we are interested is the condition of the state variable (population values) at various points in time. The output will be presented in graphical form with the x-axis being time and the y-axis being population.

Output from the model at time = 0 years (January 1, 2005) is represented in Figure 30. The starting condition of the model is a population of 4,690 people with 83 births and 60 deaths per year. Figure 31 represents output from the model at the time = +25 years (2030) condition with a population of 5,299 persons. Figure 32 represents output from the model at the time = +50 years (2055) condition on January 1, 2055 with a population of 5,987 people with 106 births and 70 deaths per year.

In addition for providing the answer to the initial question, the model can also be used to explore other scenarios. For example, reaching the goal of 10,000 persons on the island was stated as one of the goals for Montserrat's redevelopment. One conclusion that can be drawn from this modeling exercise is that if Montserrat could somehow be closed off with no persons entering or leaving the population, and the birth rate and lifespan remain at 2005 values, the island's population will not reach 10,000 persons until the year 2161 (see Figure 33).

Simulation @ Time = 0 years *(Initial Values)*

Simple Montserrat Population Scenario Table

Time	Births	Deaths	Population
1/1/2005	81.98 ppl/yr	60.13 ppl/yr	4,690.00 ppl

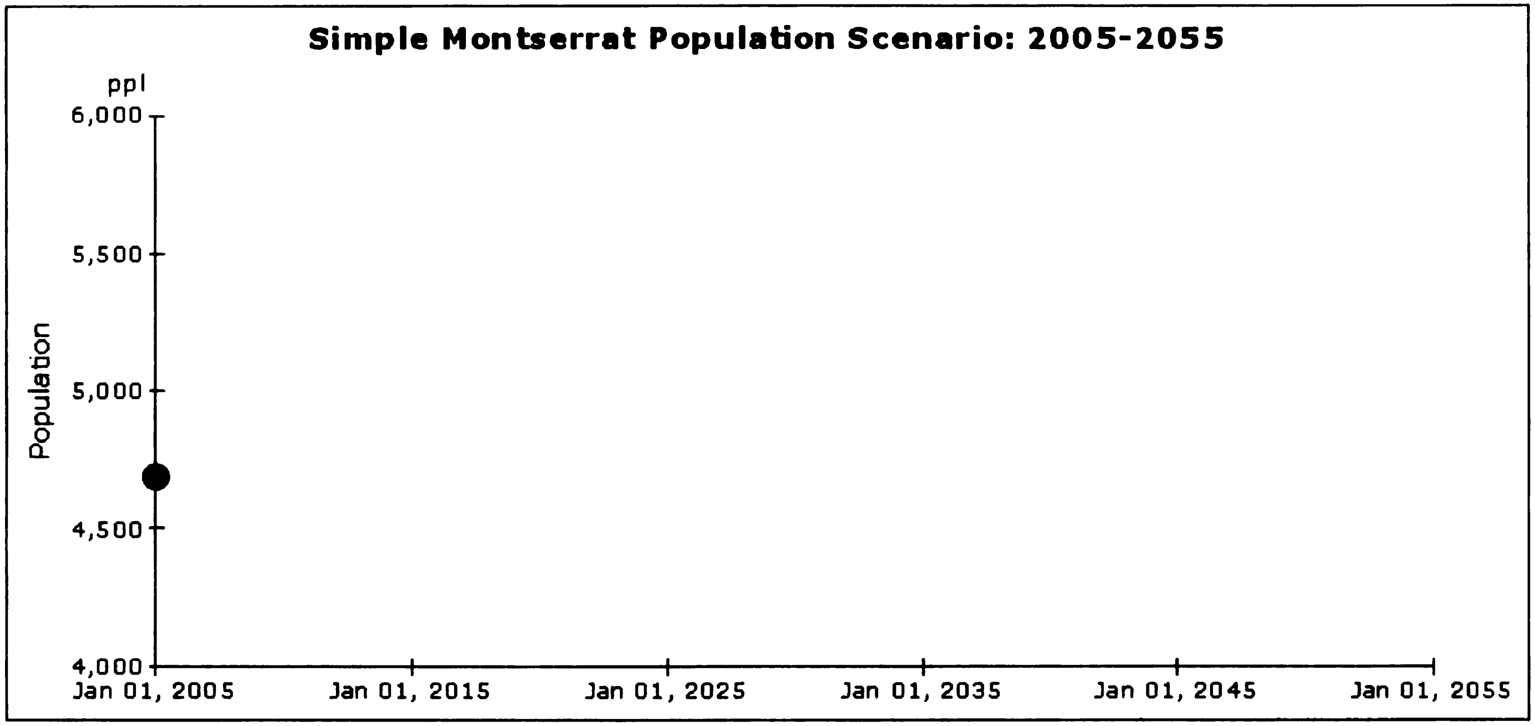


Figure 30. Output From Population Model at T= 0 years

Simulation @ Time = +25 years

Simple Montserrat Population Scenario Table

Time	Births	Deaths	Population
1/1/2030	92.08 ppl/yr	67.54 ppl/yr	5,267.99 ppl

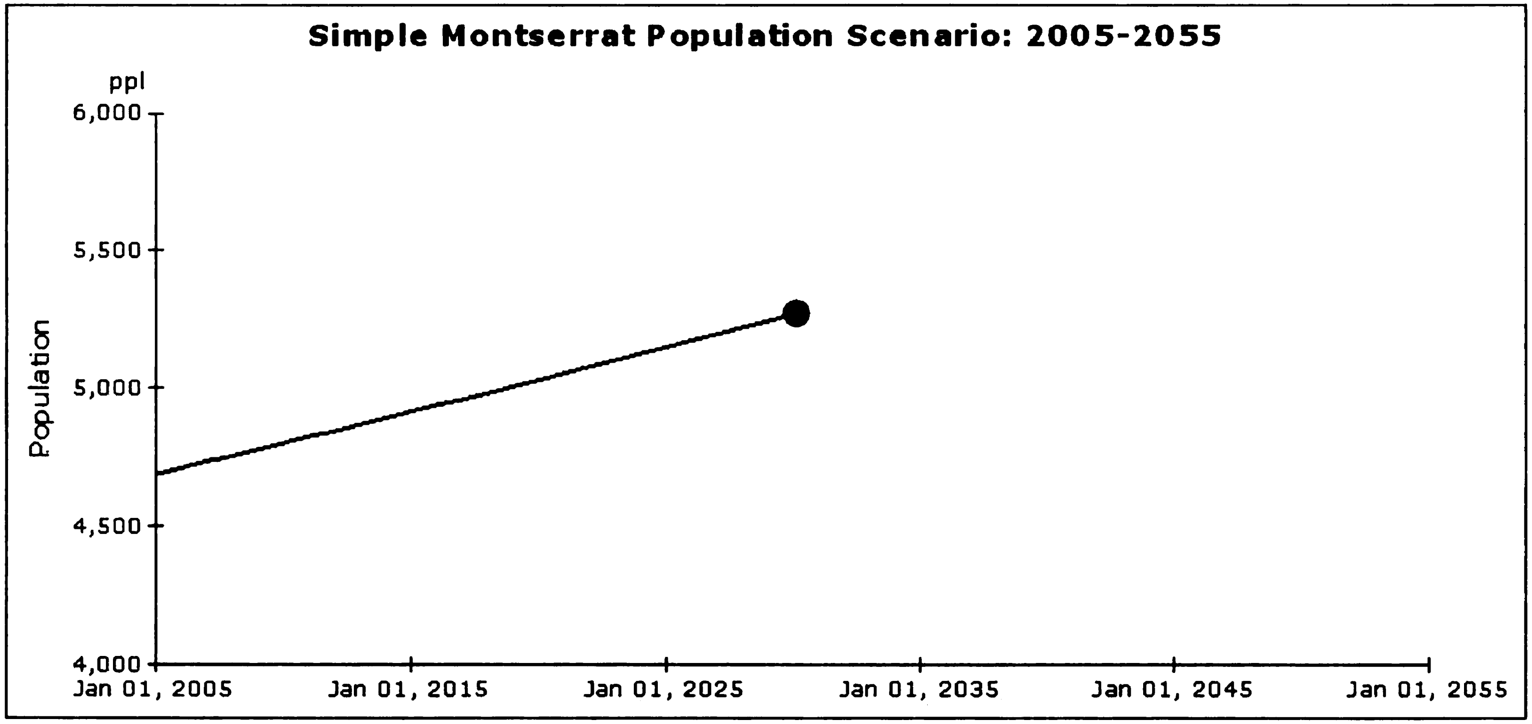


Figure 31. Output From Population Model at T= +25 years

Simulation @ Time = +50 years *(end value)*

Simple Montserrat Population Scenario Table

Time	Births	Deaths	Population
1/1/2055	103.43 ppl/yr	75.86 ppl/yr	5,917.21 ppl

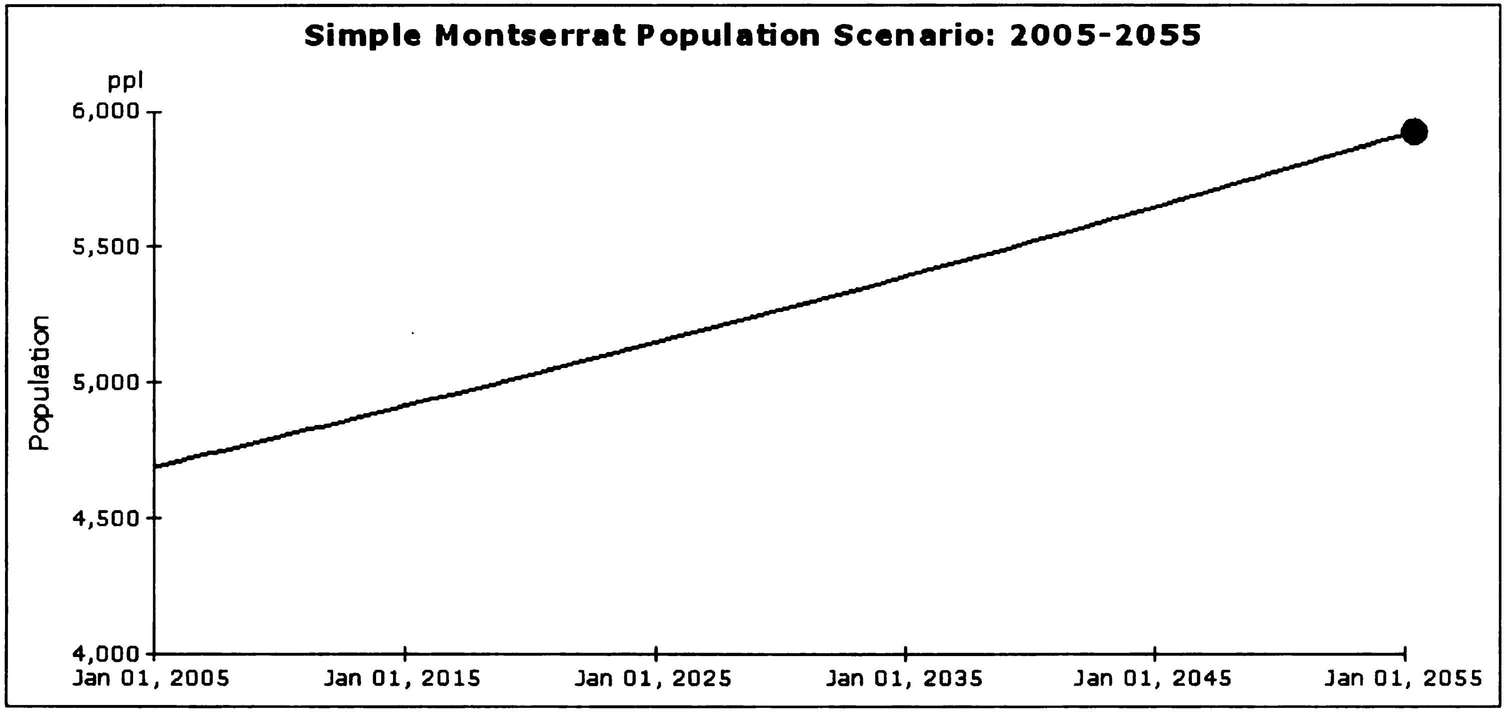


Figure 32. Output From Population Model at T= +50 years

Simulation @ Time = +156 years *(Experiment)*

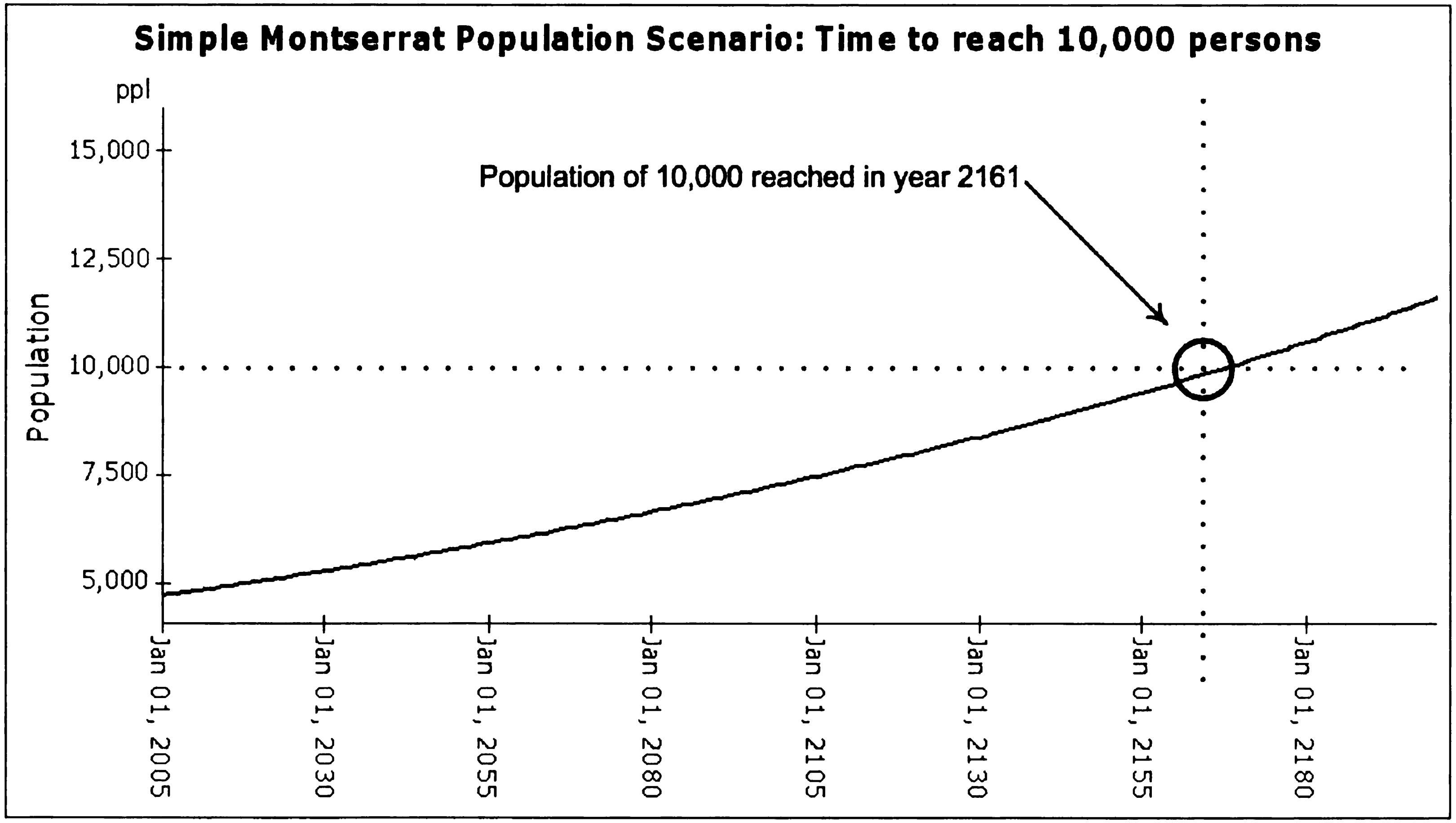


Figure 33. Output From Population Model at T= +156 years

CHAPTER FIVE

THE MONTSERRAT URBAN AND RISK MODEL

5.1 Introduction to the Model

The Montserrat Urban and Risk Model is the name given to the system dynamics model in this study. This study takes an urban model developed by Forrester and others and adopts it to the case of Montserrat. To expand on the basic urban model, this study integrates geographic and risk components. This chapter discusses various aspects the urban model, provides a description of the geographic and risk components of the model, and closes a stylized depiction of the Montserrat Urban and Risk Model.

5.2 Urban Dynamics and the Montserrat Model

The basic structure of the Montserrat Urban and Risk Model is based on urban dynamic models as first developed by Jay W. Forrester in the late-1960s. This section first explains the basic premises of urban dynamic modeling. The version of the urban model applied in this study is presented by looking at the sectors of the model individually and by depicting the main causal loop diagrams in the model. This section concludes with a depiction of the entire urban model.

5.2.1 Urban Dynamics

Dynamic models offer a means of coping with the complexity inherent in a system. When systems theory takes shape as a simulation model, its behavior precipitates discussion, and brings out additional supporting and sometimes contradictory information that adds to the understanding of the system (Forrester, 1969).

Urban dynamics is an outgrowth of industrial dynamics. Forrester's industrial dynamics addresses industrial management in terms of designing and controlling an industrial system. To be effective, Forrester said that management science must evolve effective methods to analyze the principle interactions among all the important connections of a company and its external environment. Based on that premise, industrial dynamics was defined as a method of systems analysis related to management dealing with time-varying interactions between parts of the management system (Forrester, 1961). Industrial dynamics views systems as feedback processes having a specific and orderly structure and from that structure particular dynamic behavior arises. Through computer simulation, the dynamic characteristics of the system are revealed. By changing the guiding policies in the system, one can see how behavior of the actual system may be modified (Forrester, 1961) .

When considering urban dynamics, it is important to place the development of the method in the context of the times in which it was developed. In late-1960s, the nation's urban centers were facing complex issues of decay. As many city cores were in decline, areas outside of cities were growing. The myriad of problems facing cities was difficult to conceptualize. In applying the concepts of industrial dynamics to the urban dilemma, Forrester asked whether the measures that had been taken to stem the decay of cities had not in fact intensified the decay (Forrester, 1969). Looking at urban management strategies ranging from urban renewal, to freeway construction, to housing policy, it can be argued that well-meaning urban management strategies actually intensified the decline of cities. A premise of urban dynamics is that past solutions became less successful than their supporters might have anticipated, and in a few cases these solutions had became counterproductive. Forrester argued that a re-examination of the problems facing cities was needed, he suggested that system dynamics modeling methods were a way to re-examine the problem. While Forrester's models provided conclusions that were a matter of debate, he offered his analysis in the spirit of challenging common assumptions as he thought such analysis would prove useful in the battle to save America's cities (Forrester, 1969) .

Urban dynamics models address the growth processes of urban areas by creating a system of interacting people, housing, and businesses. As an area develops, its land area fills, and the process of aging causes stagnation. As the urban area moves from the growth phase to the equilibrium phase, the population mix and the economic activity change. Unless there is continuing renewal, the filling of the land available for development coverts the area from one marked by innovation and growth to one characterized by aging housing and declining businesses. If renewal is to succeed and a healthy economic mix is to continue, the natural processes of stagnation must not run its normal course. However, the interactions between economic and social activity are so complex that intuition alone is of limited usefulness in devising policies to prevent the decay of cities (Alfeld and Graham, 1976).

5.2.2 Montserrat Urban Model Components

A primary component of the Montserrat Urban and Risk Model is the urban component. In creating the Montserrat Urban and Risk Model, the urban component of the model was developed by using components of the urban models developed by Forrester (Forrester, 1969) and interpretations of those models by Alfeld and Graham (Alfeld and Graham, 1976). The remainder of this section explains and depicts the population, housing, and business structure components of the model, discusses the urban push and pull multipliers, presents the main causal loop diagrams for the model, discusses overall model limitations, and presents the entire urban model.

5.2.2.1 Population Component

In the population component of the model, the state variable is population. The total population of the island is controlled by two types of rates: natural increases and decreases (births and deaths) and migration (in and out).

The annual amount of births and deaths depend on the normal fractional rates of both births and deaths and the population. In the model, a greater number of people results in higher birth and death rates.

Migration is defined as continual flows of people in and out of an area. Similar to population, the migration values are determined by both the normal fractional rates of in- and out-migration and the population.

Figure 34 illustrates the population sector model as it is depicted by the Powersim system dynamics modeling software. Appendix 1 provides a detailed listing of the equations, values, and assumptions on which the model is based.

The population model is adapted from the POP1 and POP2 urban models developed by Alfeld and Graham (Alfeld and Graham, 1976). These models were based on Forrester's original urban models (Forrester, 1969).

5.2.2.2 Housing Component

Building on the population component of the model, the housing component uses housing availability to modulate migration into and out of an area.

The state variable in the housing component of the model is housing stock. Housing is increased by construction and decreased by demolition. The housing

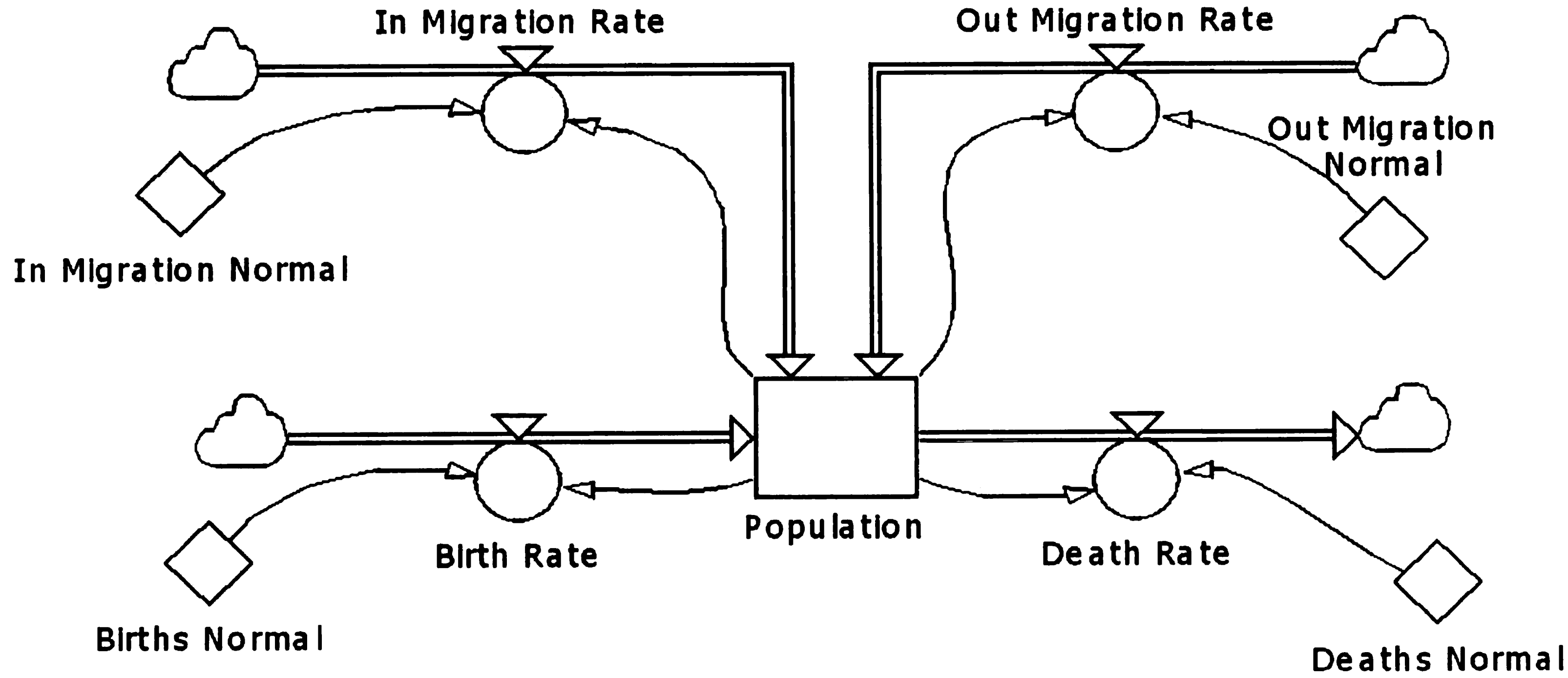


Figure 34. Population Sector of Model

construction rate is directly related to the houses to households ratio, which acts as a simple measure of housing availability per person. That measure aggregates more specific housing indicators such as price, vacancy, and other factors related to housing surplus or housing scarcity.

Another key component of the housing sector is the land fraction occupied. Land fraction occupied is equal to the land area occupied by structures divided by the total land area in the model. Land fraction occupied acts through the housing land multiplier and the housing construction multiplier to influence the housing construction rate per acre.

A potential problem on the island will be housing stock decline. Immediately after the disaster, housing was quickly constructed to shelter those persons who were displaced from areas in close proximity to the volcano. This temporary housing was located in a zone of lesser risk that is known as zone 2 (the three geographic zones on Montserrat will be discussed later in the chapter). Such temporary housing will physically deteriorate quickly and result in an increased demolition normal value for housing in areas where such temporary housing is predominate. In terms of sustainability, it is suggested that planners perform a survey of the housing stock on the island with an eye towards identifying temporary housing that will deteriorate quicker, so that this type of housing could be replaced by an implementing a policy of matching the new housing construction rates to the deterioration rate of temporary housing. In post-disaster situations, it is often the case where temporary shelter needs to be constructed in emergency circumstances, but over the long-term these temporary shelters may transition into permanent housing.

In the Montserrat Urban model, specific housing stock decline assumptions were addressed by setting specific demolition rates by zone. For zone 1, the demolition rate was set to 5 houses per 1,000 per year. In zone 1, there is a higher quality housing stock. In general, little if any temporary housing was built in this zone as this zone faces the highest risk of all areas in the safe zone. For zone 2, the demolition rate was set to 25 houses per 1,000 per year. This demolition normal rate is higher, since zone 2 has many temporary structures which will physically deteriorate quicker than those in zone 1. For zone 3, the demolition rate was set to 20 houses per 1,000 per year. In zone 3, some temporary housing was constructed, but overall more new permanent houses are constructed in this zone. Zone 3 has a mix of some temporary housing along with more new permanent housing, as the housing goal for the island is to build up a higher quality more permanent housing stock in zone 3.

Figure 35 illustrates the housing sector model as it is depicted by the Powersim system dynamics software. Appendix 1 provides a detailed listing of values for the variables and the values reflect the assumptions on which the model is based.

The housing model is adapted form POPHOU urban model developed by Alfeld and Graham (Alfeld and Graham, 1976). These models were based on Forrester's original urban models (Forrester, 1969).

5.2.2.2.1 Housing Component Multipliers

An important part of the both the housing and business structure components of the urban models is the multipliers or table functions. Multipliers are auxiliaries that reflect the influence of the ratio of two variables on a rate or other auxiliary. In the functioning of the multipliers, depending on the value of the ratio which serves as input

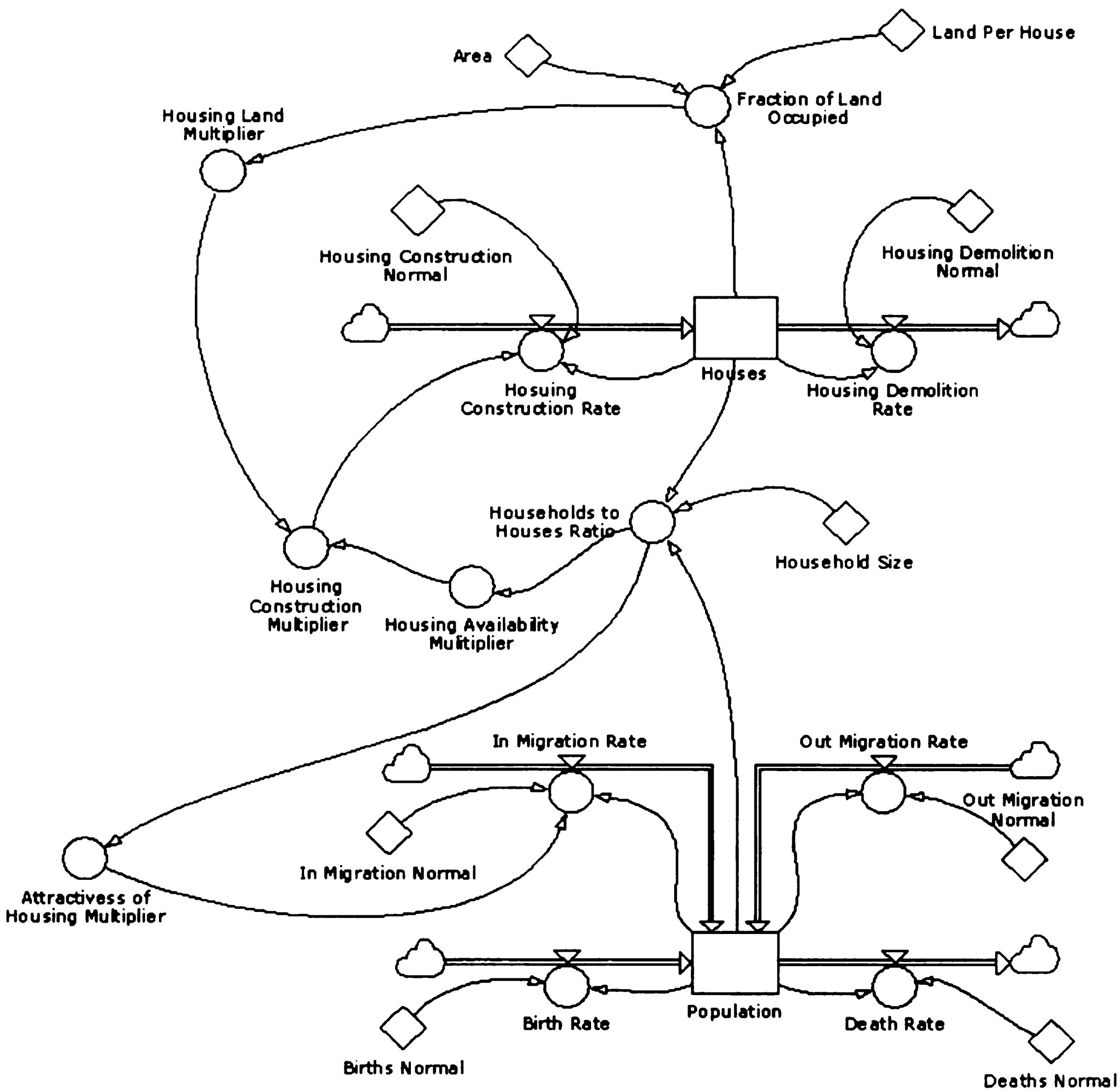


Figure 35. Housing Sector of Model

to the multiplier, the software instructs the computer to find the corresponding value on the graph and use that value as the multiplier value. The multipliers are essential in reflecting push and pull influences in the model.

In the housing component of the model, there are three such multipliers: the housing availability multiplier (HAM), the housing land multiplier (HLM), and the attractiveness of housing multiplier (AHM). These multipliers are drawn from the POPHOU urban model as developed by Alfeld and Graham (Alfeld and Graham, 1976). Appendix 2 depicts the values for these housing multipliers in the form of graphs.

5.2.2.3 Business Structure Component

Again, building on the population component of the urban model, the business structure sector reflects economic conditions influencing the model. The state variable of business structures serves as a proxy for considering economic development factors. Similar to housing, the number of business structures is added to by construction and subtracted from by demolition.

Again, the land fraction occupied plays a key role in influencing the number of business structures in the model. Land fraction occupied acts through a business land multiplier, and a business construction multiplier, to eventually influence the business construction rate.

Given the post-disaster situation on the island, residents are not self-sufficient. They depend on jobs as an income source to obtain money for basic and other needs. In the model, the variable jobs serves in a highly aggregated sense to include all employment related to the production and maintenance of societal wealth. Jobs influence the rate of business structure construction by acting through the labor force to jobs ratio, business labor force multiplier, and business construction multiplier.

In relation to the population components of the model, the attractiveness of jobs multiplier acts to influence the in-migration rate. The multiplier modulates the rate of in-migration in response to employment conditions represented by the labor force to jobs ratio.

Figure 36 illustrates the business structure sector as it is depicted by the Powersim system dynamics software. Appendix 1 provides a detailed listing of values for the variables and the values reflect the assumptions on which the model is based.

The business structure component of the model was adapted from the BSNSS2 urban model developed by Alfeld and Graham (Alfeld and Graham, 1976). These models were based on Forrester's original urban models (Forrester, 1969) .

5.2.2.3.1 Business Structure Component Multipliers

Similar to the housing component of the model, multipliers are used as auxiliaries that reflect the influence of the ratio of two variables on a rate or other auxiliary. The multipliers are essential in reflecting the push and pull of jobs and business structures on population and housing.

In the business structure component of the model, there are three such multipliers, the business land multiplier (BLM), the business labor force multiplier (BLFM), and the attractiveness of jobs multiplier (AJM). These multipliers are drawn from the BSNSS2 urban model as developed by Alfeld and Graham (Alfeld and Graham, 1976). Appendix 3 depicts the values for these business structure multipliers in the form of graphs.

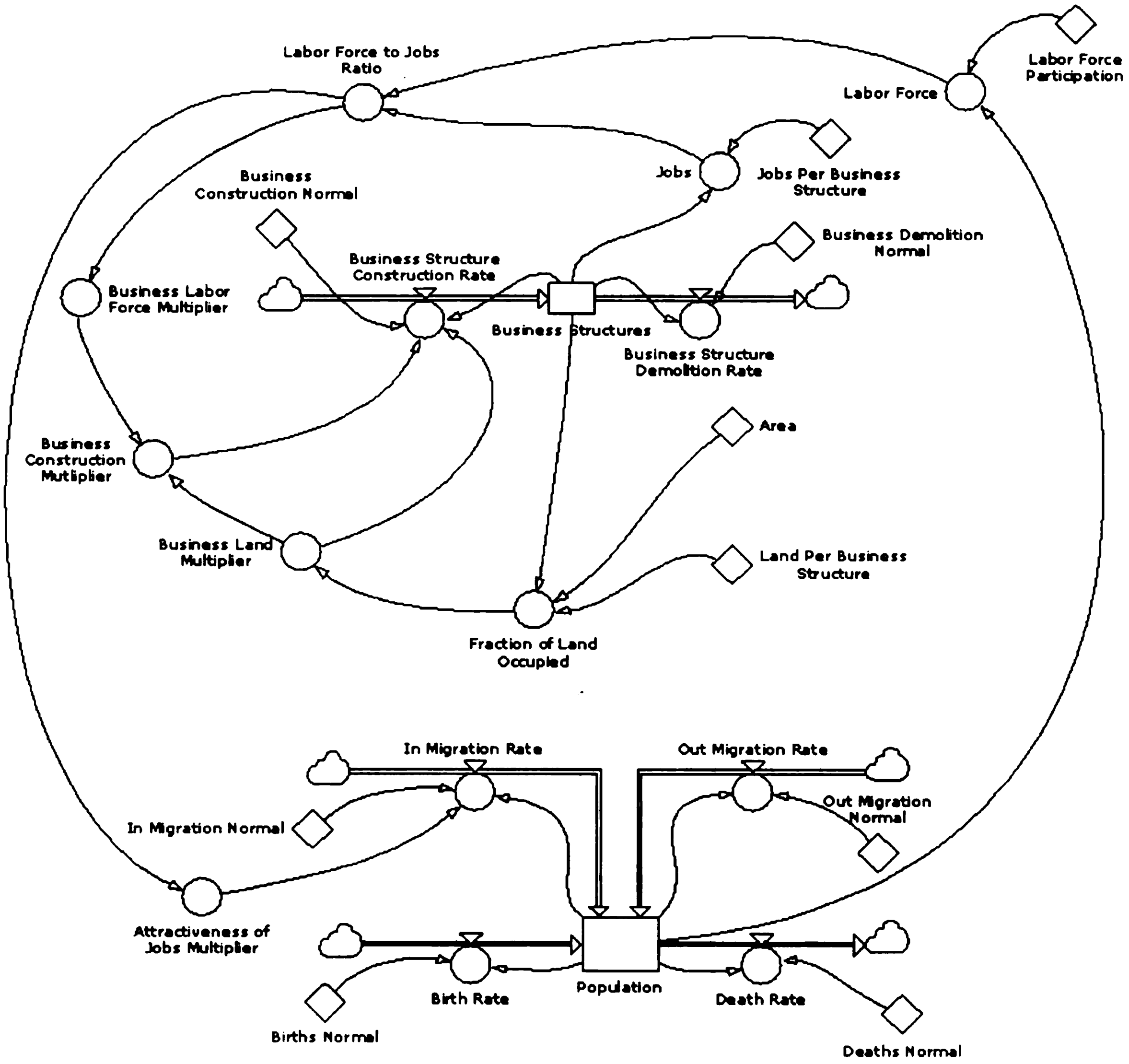


Figure 36. Business Structure Sector of Model

5.2.3 Urban Model Causal Loop Diagrams

The key causal loop diagrams for the Montserrat Urban model are the population, housing, and business structure causal loop diagrams. Causal loop diagrams are maps showing the causal links among variables with arrow from a cause to an effect (Sterman, 2000).

Figure 37 illustrates the causal loop diagram for the population sector of the model. The causal loop diagram shows the feedback processes that control the population level. The diagram contains two reinforcing loops and three balancing loops. For example, a reinforcing loop is illustrated in the population and in-migration loop. With a constant in-migration factor, an increase in population leads to an increase in in-migration. An example of a balancing loop is the population and out-migration relationship which reflects the effect of in-migration on the population. Given a constant increase in population, there will be greater out-migration which reduces the population.

Figure 38 illustrates the housing causal loop diagram. This diagram illustrates the feedback processes that control the number of houses. There are three balancing loops and one reinforcing feedback loop. A key balancing loop is the housing, land fraction occupied, housing due to land availability, and construction rate loop. That loop illustrates the relationship between housing and land area. An increase in the number of houses adds to the land fraction occupied, thereby reducing the housing construction due to land availability. This feedback reduces the construction rate. The one, and only, reinforcing loop in the housing causal loop diagram illustrates how the number of houses affects the construction rate. With the construction factor constant, an increase in the

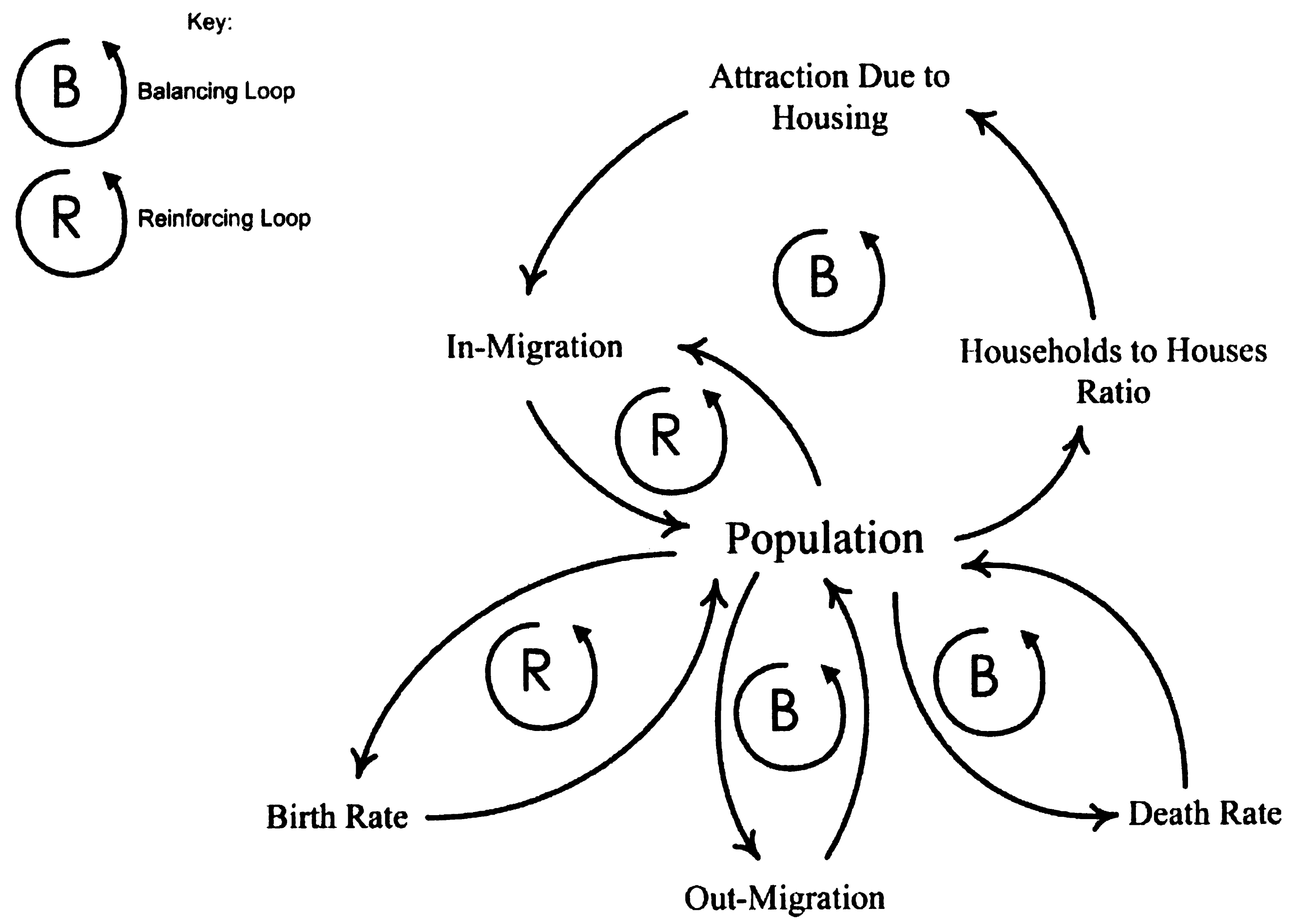


Figure 37. Population Causal Loop Diagram

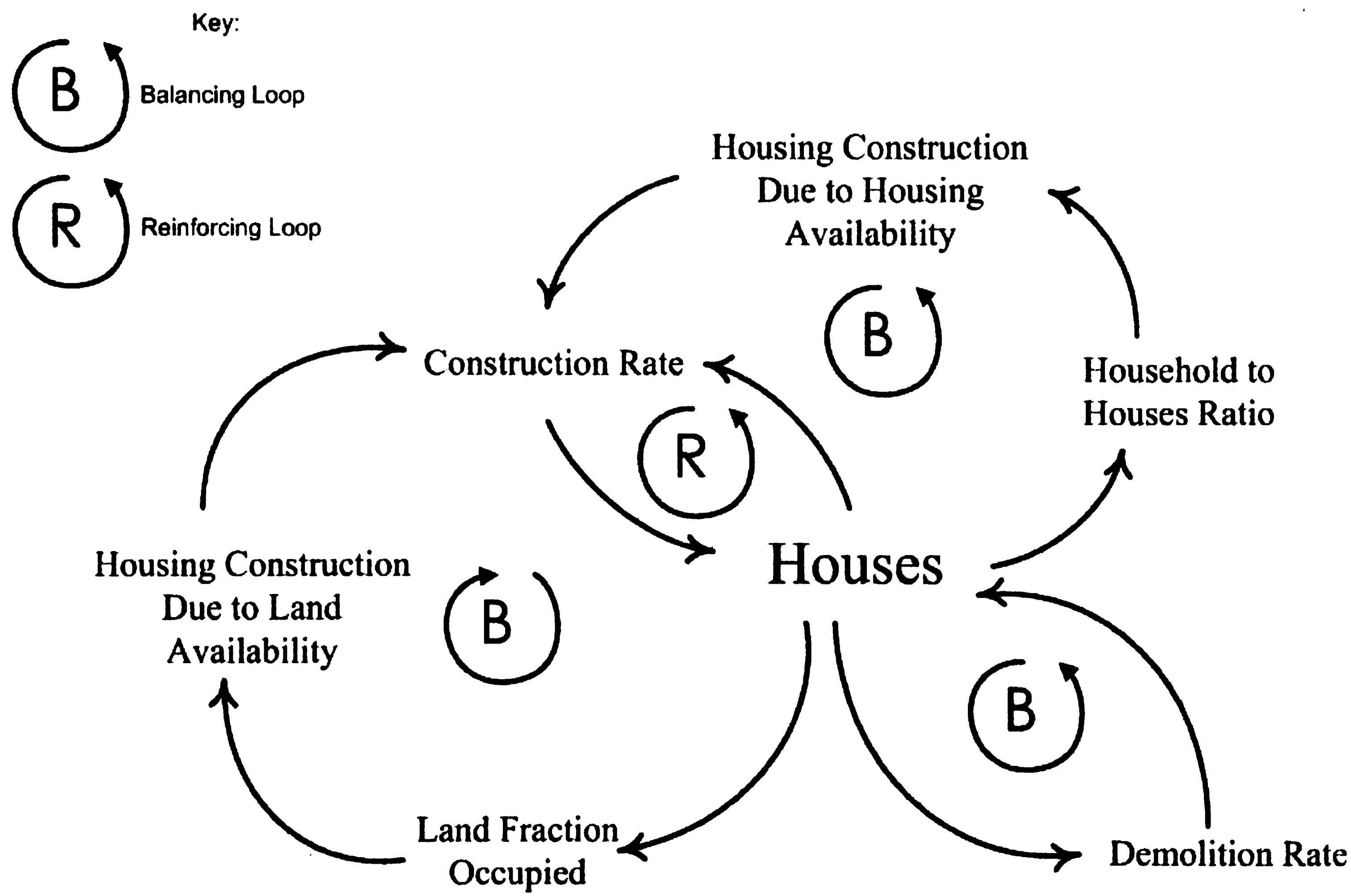


Figure 38. Housing Causal Loop Diagram

number of houses boosts the construction rate, resulting in further increase in the number of houses.

Figure 39 illustrates the business structure causal loop diagram. The business structure causal loop diagram depicts the feedback processes that control the number of business structures. In the causal loop diagram, there are three balancing loops and one reinforcing feedback loop. A key balancing loop links the business structures, labor force to jobs ratio, business structures due to construction due to job availability, and the construction rate. This loop depicts the relationship between jobs and population. An increase in the number of jobs decreases the labor force to jobs ratio, which in turn acts through the business structures due to the job availability variable to reduce the housing construction rate. There is only one reinforcing loop in the business structures causal loop diagram, and it illustrates how the number of business structures affects the construction rate.

5.2.4 Overall Urban Model Limitations

An overarching limitation of the Montserrat Urban and Risk Model is that it assumes a constant amount of overseas aid to maintain life on the island and support future growth. In Chapter 2, the section "Post-Disaster Economic Uncertainty on Montserrat" highlights some of the economic concerns Montserrat faces. Clearly, portions of the population on the island are supported by a social welfare program that developed in a large part due to the displacements caused by the volcanic crisis. The model assumes that British aid will remain at the same level as the present, and that the aid will increase to levels necessary to support population growth and infrastructure expansion. At the time the model was constructed, there were no official indications that

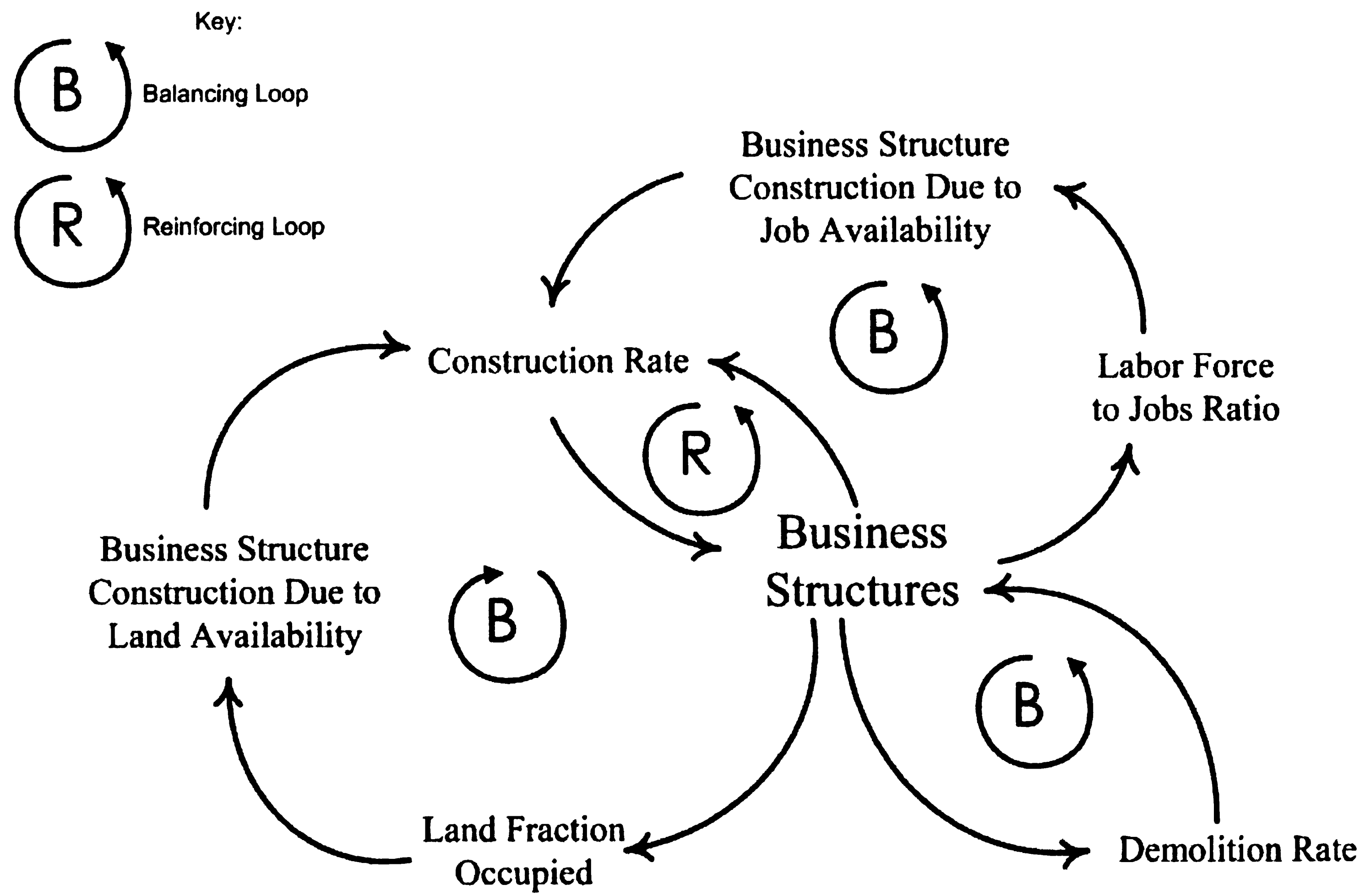


Figure 39. Business Structures Causal Loop Diagram

aid to Montserrat will be reduced, so this economic factor was not reflected in the model. However, if in the future a reduction of aid takes place, the model will have to be reconsidered to reflect the impact of that change.

A second overarching limitation of the model is its limited ability to provide results relative to judging the sustainability of the island. Specifically, resources are needed to support the population on the island. While the model takes into account the land resource, other physical resources such as energy, food, potable water, fisheries, forestry, raw materials, etc. are needed to sustain life on the island. As the volcanic disaster devastated the southern two-thirds of the island, much of the island's physical resource base was lost. While it is obvious that in the time period immediately after the disaster, many resources will need to be imported to the island, it is expected that as the disaster recovery proceeds, the island will become increasingly self-sufficient. The model assumes that resources are present to both support the base population on the island and to support future growth. The model does not take into account the potential for resources shortages or how sustainability considerations may limit activities on the island. When creating the model, through both a combination of native resources and imported resources, there were no resource shortages on the island. However, in the future, resource limitations may become a factor in limiting growth on the island. If that were the case, the key resources causing the limitations would need to be identified and a resource sustainability component of the model would need to be created.

5.2.5 Entire Urban Component

The population, housing, and business structure sectors of the model were combined to create the model depicted in Figure 40. Land fraction occupied is a key

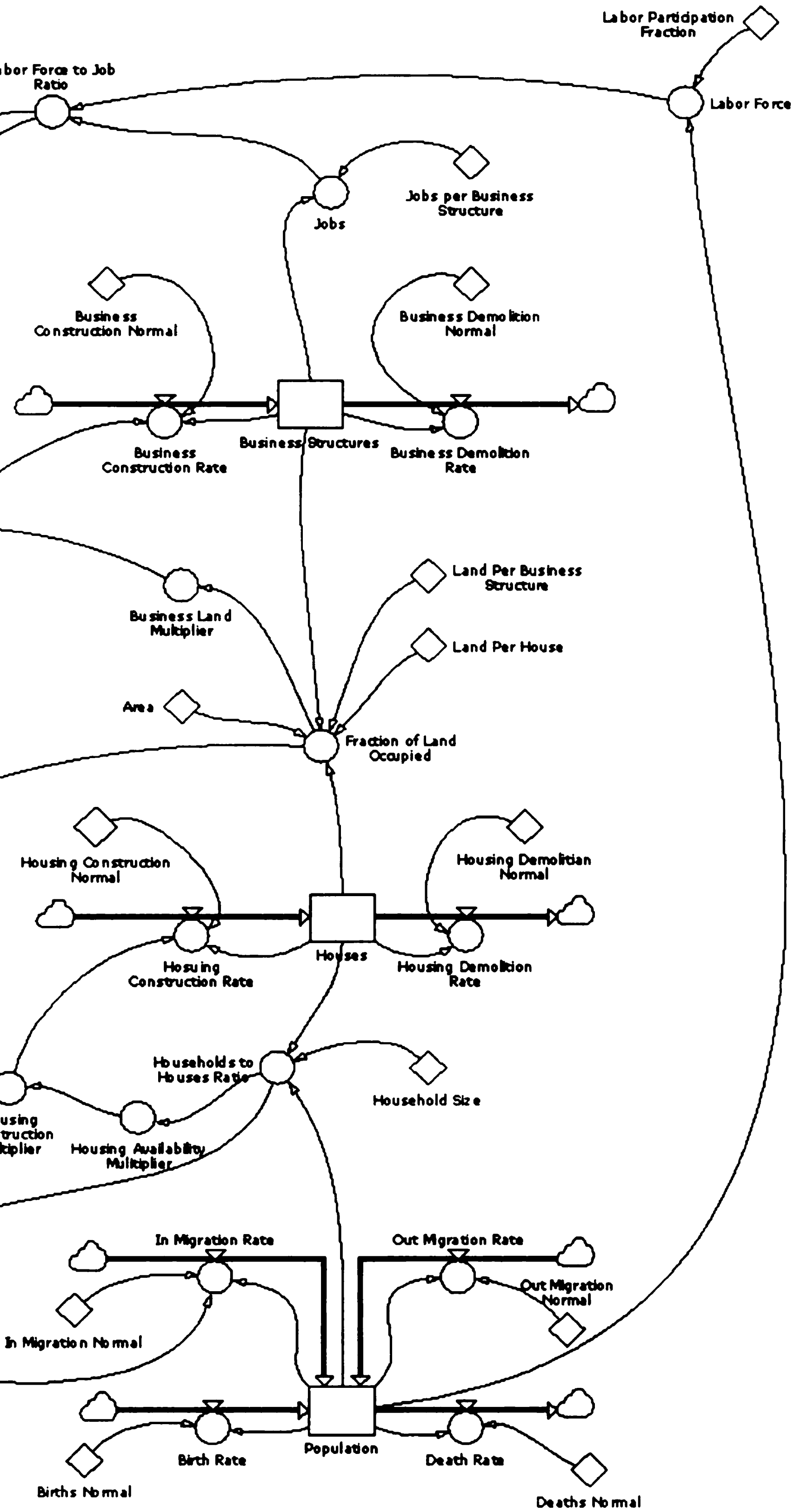


Figure 40. Entire Urban Sector of Montserrat Urban and Risk Model

variable linking business structures and housing. Population and housing are linked through the households to houses ratio and the attractiveness of housing multiplier. Both jobs and housing influence population by an attractiveness multiplier feeding into the in-migration rate.

The following sections of this chapter describe how the urban component of the model was further adapted to the Montserrat case by adding geographic and risk components.

5.3 Geographic Components of the Montserrat Urban and Risk Model

During the volcano crisis, Montserrat was divided in risk zones as explained in Chapter Two. The southern two-thirds of the island is an exclusion surrounding the volcano. It too dangerous to inhabit and off limits to all occupation. No modeling took place for this zone. The northern one-third of the island is a safe zone, which for the purposes of this study is sub-divided into three zones. Figure 41 depicts the geographic zones for the entire island. This section discusses the geographic assumptions on which the model is based, specifically, assumptions regarding land area for each zone, assumptions regarding the characteristics of each zone, and the assumptions regarding population movement between the zones.

5.3.1 Land Area Assumptions

The land area for the entire island is 39.6 square miles (25,344 acres). Of that total acreage 9,738 acres (or 38% of the island's total land area) is in the safe zone. These figures were drawn from data in the Montserrat Physical Development Plan (Physical Planning Unit, 1999). It should be noted that if one were to survey the island in 2005, the exact division of acreage between the exclusion zone and the safe zone may

Montserrat: Entire Island

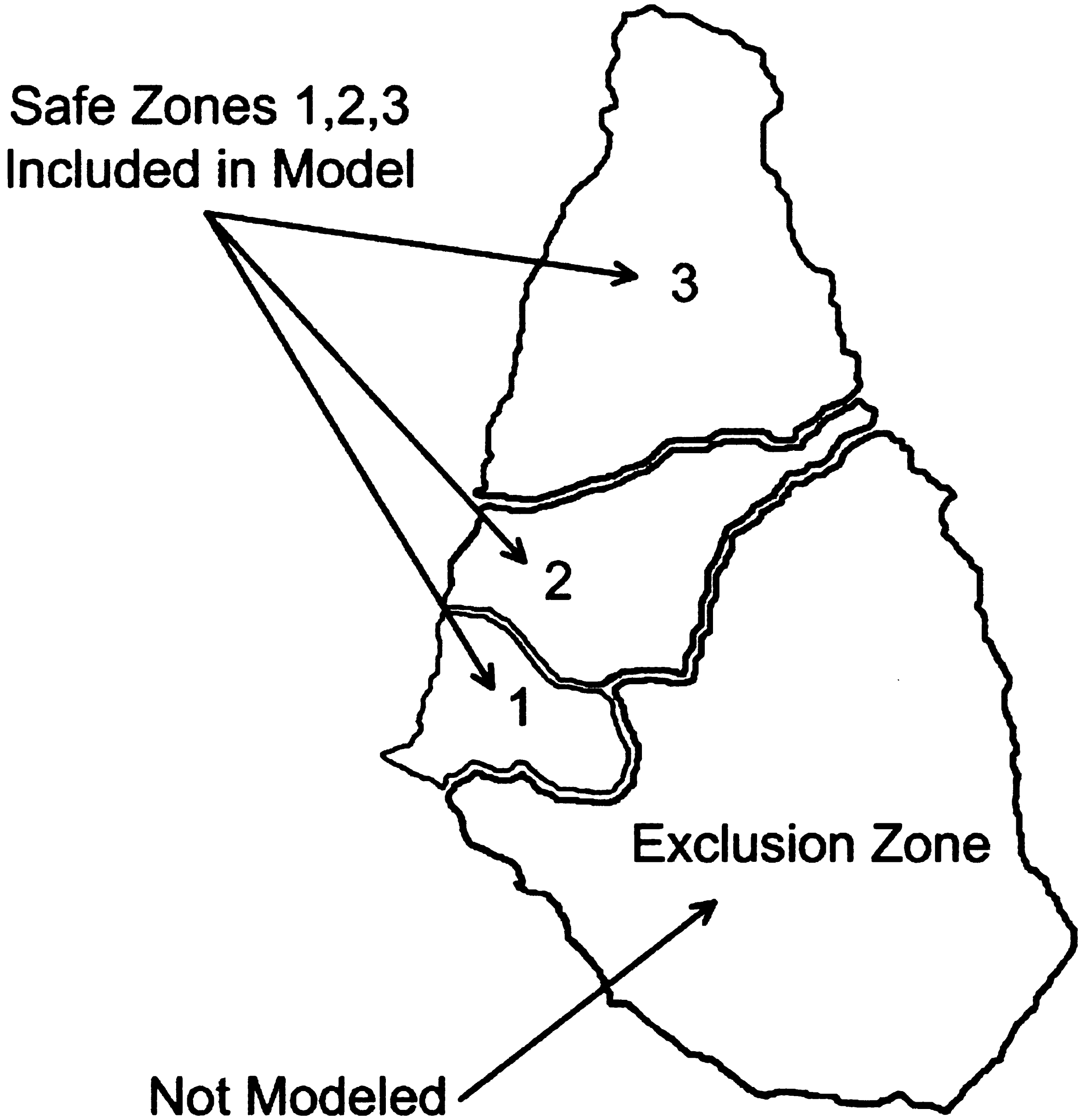


Figure 41. Montserrat Geographic Zones

differ from the figures used in this study. However, the approximations applied are within the range of reasonable assumptions for considering the land area available for development on Montserrat.

Of the land available for development in zones 1, 2, and 3, due to environmental constraints only a portion of the land is actually useable. Environmental constraints which limit or prevent development are factors such as climatic suitability, soil suitability, and soil erosion hazards. On Montserrat, there are two hill complexes in the safe zone, the Centre Hills and Silver Hills. There is also varied terrain along the eastern coastal zone. When new development is considered for the northern safe zone, a land capability analysis should take place to determine what limitations may exist in regards to the physical dimensions of the land. Frameworks for development planning have been created that can be applied to considering planned development in rural areas (Staveren and Van Dusseldorp, 1980).

For this study, assumptions were made regarding the physical dimensions of the land that limit development, such as and unsuitable soils. These assumptions were made based on island's topography and data from the Montserrat Physical Plan. In the northernmost zone, zone 3, the assumption was made that 35% of the area would not be available for development due to environmental constraints. Zone 2 is closest to an area of Montserrat known as the Centre Hills and it is assumed that if a survey of developable conditions took place 60% of the land area would be unsuitable for development. In zone 1, approximately 50% of the land area would be unsuitable for development as it is closer to hills and steep slope areas in the center of the island, but areas near the coast would be suitable for development. Figure 42 depicts the three areas of the safe zone along with the

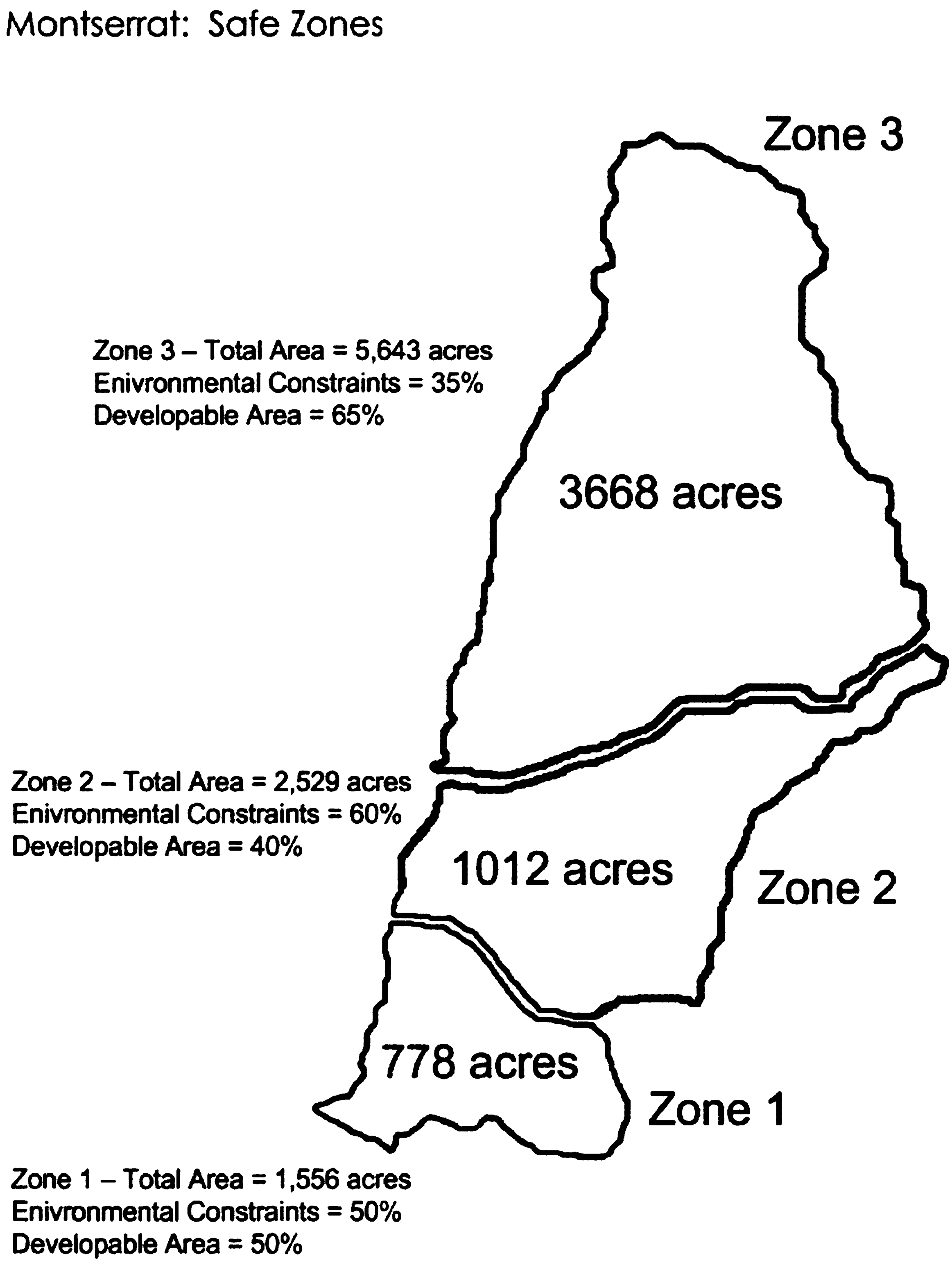


Figure 42. Developable Land Area by Zone

data concerning the total land area available for development. The amount of land area available for development acts as the area value for each zone.

5.3.2 Assumptions Concerning Characteristics of the Zones

Each zone has its own unique characteristics. Assumptions were made to set these characteristics based on information provided in Montserrat's physical development and other literature referenced in Chapter 2. The main assumptions made concerning the nature of land use in the zones and key initial values assigned to variables in the model are described in this section's narrative. For a more complete description of the model's variables see Appendix 1. Figure 43 provides a graphical summary of the key land use characteristics of the zones. In zone 1, the land use is residential, so population and housing are modeled for that zone. In zone 2, the land uses are housing and large business structures, therefore population, housing, and business structures are modeled for zone 2. Land uses in zone 3 are housing and small business structures, therefore population, housing, and business structures are modeled for zone 3.

For zone 1, the land area is assumed to house 25% of the island's total population or 1,173 persons. While this zone has the least land area, it also has the highest housing density. Prior to the volcanic crisis, zone 1 was on the outskirts of the larger urban area that was destroyed during the volcanic events. The residential development in zone 1 is assumed to be at 5 houses per acre and each house has a household size of four persons per house. The normal construction rate was set at 100 homes per 1,000 per year and the demolition rate was set to be low at 5 homes per 1,000 per year since the housing stock in this zone is relatively new.

Montserrat: Safe Zones

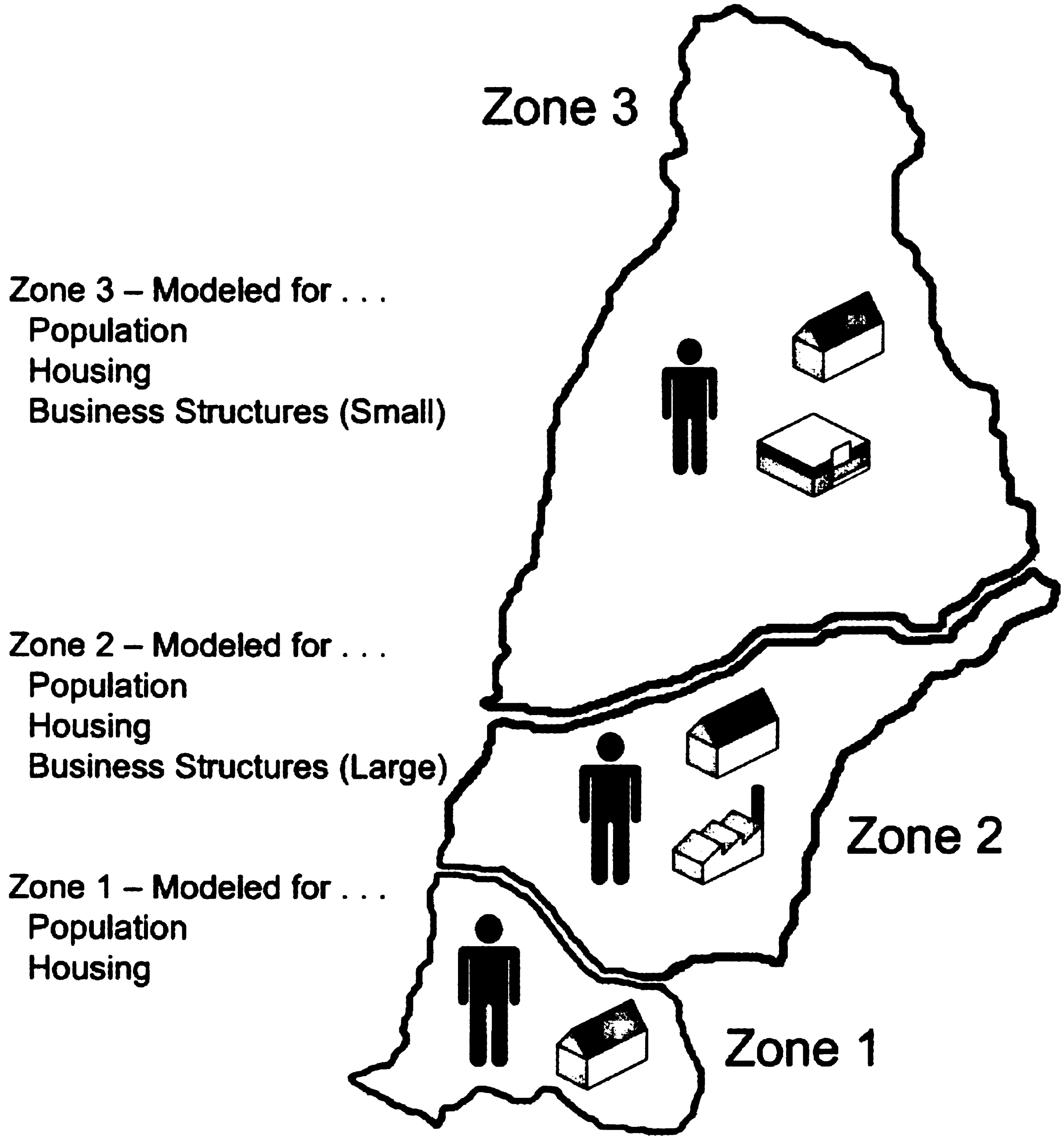


Figure 43. Zone Land Use / Model Characteristics

Zone 2 is comprised of both housing and business structures. This zone houses 30% of the island's total population or 1,407 persons. As this portion of the safe zone is at a lesser risk (see risk section) the construction rate is higher than zone 1 at 300 homes per 1,000 per year. However, due to the existence of some temporary homes of lesser quality, the demolition rate is higher than that in zone 1 with the value set at 25 homes per 1,000 per year. Similar to zone 1, four persons per household is the household size however, the development is less dense than zone 1 with 4 houses per acre set as the density. Regarding business structures in zone 2, these businesses comprise larger structures such as factories that occupy more land per business structure (1 acre per business structure) but also provide more employment per business structure (25 jobs per business structure). As such businesses are hard to attract to the island, given the limited resources and small economy, the initial number of these businesses is set at a low value of 16. The normal construction rate (8 per 1,000 per year) is set to be lower than the demolition rate (25 per 1,000 per year) as it is often the case that small island's economic conditions will bring about situations where such business structures become obsolete at a rate which is faster than the rate at which such enterprises can be attracted and constructed. Implicit in the assumptions of the characteristics of the business structures in zone 2 is a policy decision to locate larger facilities exclusively in zone 2. Given the fact that a smaller number of these facilities with a larger number of employees per facility exists in zone 2, in the event that conditions in the zone deteriorate to the point where evacuation is necessary it will be easier to evacuate a smaller number of large facilities, than a larger number of smaller facilities (such as in zone 3).

Zone 3 is the largest zone with the highest population and the greatest number of houses and business structures. The northernmost zone has the highest population at 2,110 persons or 45% of the island's total population. The initial number of houses in zone 3 is set at 1,620 with an average person of household value of five (higher than the other zones), a high construction rate (400 per 1,000 per year), a low demolition rate (20 per 1,000 per year), and a housing density of four homes per acre. These rates are reflective of the situation that zone 3 has the lowest relative risk as compared to the other zones, and much of the housing stock in zone 3 is relatively new. In terms of business structures, zone 3 has a large number (230) of small business structures and they employ 5 persons per business structure. In terms of the rate of turnover of these structures, the construction rate is 10 business structures per 1,000 per year and the demolition rate is set at 6 business structures per 1,000 per year, so despite the turnover, there is a slight growth in the number of smaller business structures over time. The values used for the model in zone 3 indicate that the smaller business structures service the residential areas. Typical businesses would be small food stores, various markets, retail facilities, restaurants, and other service-orientated businesses.

5.3.3 Assumptions Regarding Population Movement

As the model divides the island's geography in 3 zones in the safe area, population flows in and out of these zones over time. This movement of population can be between zones on the island, onto the island from overseas locations, or off of the island to overseas locations.

In terms of population movement from overseas location to Montserrat, in-migration arrives at different areas. As the areas closer to the volcano are the areas where most of the population fled from, zone 1 receives a portion of that population. As zone 1 is on the outskirts of a larger urban that was destroyed, it receives 10% of the total in-migration. This zone 1 in-migration is primary due to persons returning to abandoned property they already own.

In-migration from overseas locations to zone 2 takes places for similar reasons, except zone 2 has a larger population and housing base from which to build on, therefore the in-migration rate is 20%.

Zone 3 receives a majority of the in-migration from overseas (at a level of 70%) as most persons returning to island will have had their homes and business destroyed in the exclusion zone and be returning to zone 3 to start over. Also, as zone 3 has the lowest relative risk (see the risk section), the policy for in-migration would be to direct people to live in zone 3 once they arrive on the island.

In terms of migration between the zones, once persons arrive in a zone they can migrate north, but they cannot move south. This rule was established to prevent people from relocating for areas at lower risk to areas at higher risk. In other words, if a person arrives on the island and has property in zone 1, they will not be prevented from living in the zone 1 (as it is in the safe zone), but given the situation of continued risk, once a person settles in a zone they are prohibited from moving from zones of lower risk to zones of higher risk, that is from zone 3 backwards to zone 2 or zone 1. This policy is being enforced during the 50 year time period of the model. Such a policy contributes to the goal of eventually moving as much of the population into zone 3 as possible. The rules governing movement between the zones will be examined once the 50-year modeling period has expired.

Persons who off-migrate from the island do so from zone 3, the safest zone. As these risk adverse persons relocate from dangerous zones to zones of lesser relative risk, if the risk level remains high in the zone that was perceived to be the safest, they will off-migrate to other locations. Persons moving from the island are either those who have arrived in zone three and find the conditions unacceptable of those persons who out-migrate from zone 1 or zone 2 and arrive into zone 3, and still find the conditions unacceptable.

Figure 44 depicts the in- and out-migration patterns described in the narrative.

5.4 Risk Components of the Montserrat Urban and Risk Model

Risk is the likelihood, or more formally the probability, that a particular level of losses will be sustained by a given series of elements as a result of a given hazard impact (Alexander, 2000). In terms of the model being applied in this study, elements at risk include people, houses, and business structures. In considering total risk, the following equation has been applied:

$$\text{Total Risk} = (\Sigma \text{ elements at risk}) * (\text{hazard} * \text{vulnerability})$$

where total risk consists of the sum of predictable deaths, injuries, destruction, damage, disruption, and the costs of repair and mitigation and vulnerability refers to the potential for casualty, destruction, damage, of other forms of loss with respect to a particular hazard element (Office of the United Nations Disaster Relief Coordinator, 1980).

In terms of Montserrat, risk is expressed as the probability of death, injury, or losses that will result from volcanic actions. The risk is realized through the volcanic hazard. For the purposes of this study the volcanic hazard will consist primarily of volcanic material flowing into areas which were previously untouched by the volcanic hazard. The risk is

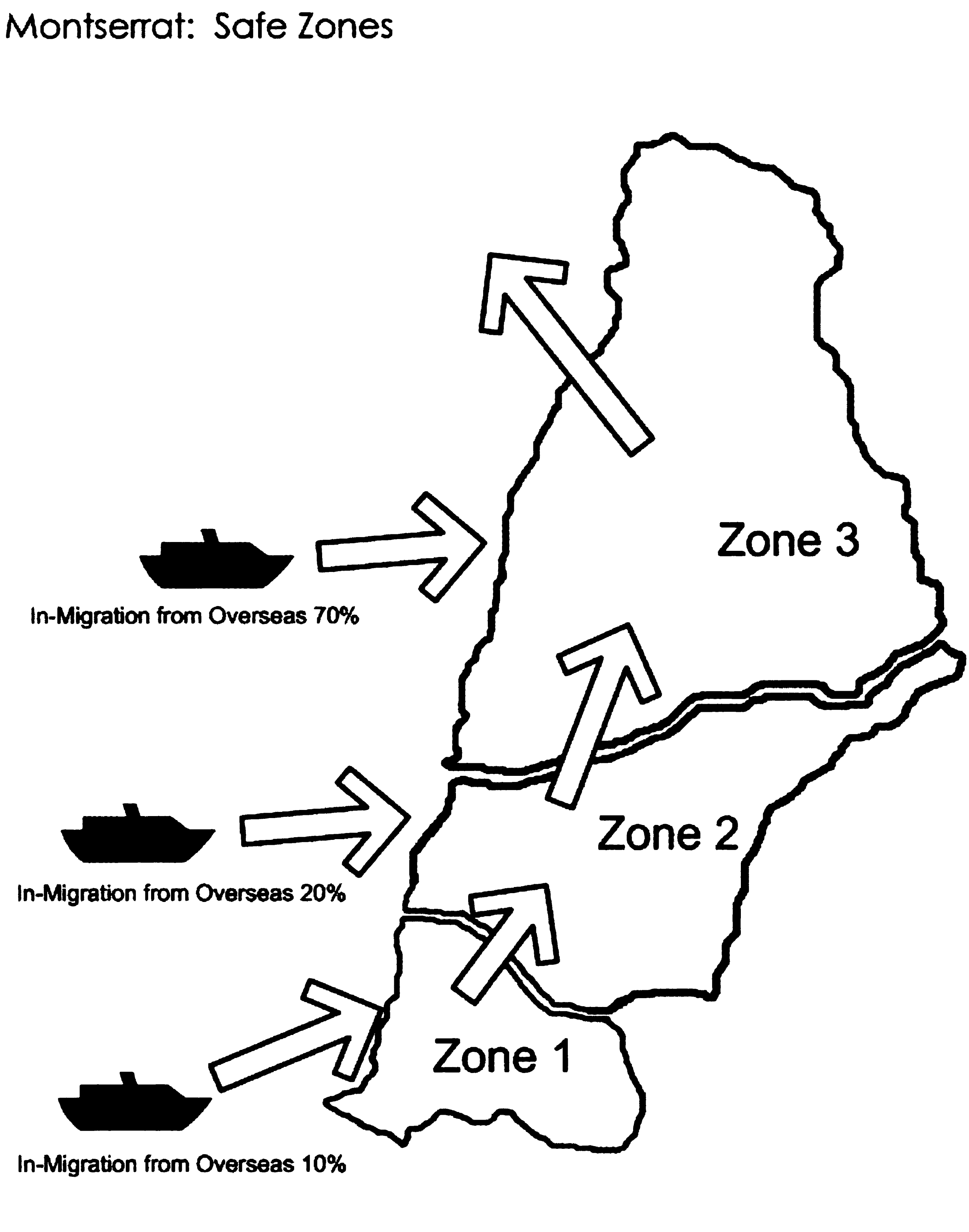


Figure 44. In and Out Migration Patterns

measured according the scale provided in Figure 45. Scientific measurements and observations of volcanic action allow for hazard and risk to be translated into quantitative values.

In order to operationalize risk in the Montserrat Urban and Risk Model, a systems model is created to generate a value of risk on a scale of zero to one. The risk that is being referred to is specifically the probability of occurrence of negative effects of the volcano on people, land, houses, business structures, or perception of the hazard. As risk is being referred to in the model, the risk implies that volcanic activity increases to the point where it begins to eject lava making land unsuitable for development. These impacts cause an increased rate of out-migration from zones where the risk level passes critical thresholds, and when risk acts through the model it reduces attractiveness and construction rates, and increases the demolition rate of both homes and business structures.

To quantify risk, arbitrary values were chosen where risk begins to effect certain elements of the model. As the value of risk increases from zero to one, risk begins to have a greater impact. Figure 45 is an illustration of values and actions illustrating what the values imply in terms of realized risk. When risk passes threshold value of 0.6 it acts as a driver launching certain functions in the model causing risk to be realized by specific actions. By experimenting with the model through sensitivity analysis, it was possible to determine the ranges in which risk had the greatest influences on model elements.

5.4.1 Differential Levels of Risk by Zone

In the Montserrat Urban and Risk Model, risk is defined as a quantity that decays over distance. That is, as one moves further away from the volcano the level of risk will

Risk Value	Impacts of Risk
0	0 % Probability of death, injuries or total losses that result from volcanic action
0.1	Low Risk Range (little, if any, likely exposure to hazards)
0.2	Background Risk level with active volcano Low Probability that losses will be sustained from volcanic action
0.3	
0.4	Medium Risk Range (as risk nears 0.6 vulnerability of people and structures increases as exposure to the hazard increases)
0.5	
0.6	Threshold Level at which there is a high probability losses will be sustained
0.7	High Risk Range (as risk nears passes the 0.6 threshold, risk takes action on elements of the model such as reducing the land fraction available for development, increasing demolition of houses and business structures, reducing the construction rate, increasing out-migration, and influencing perception by limiting in migration)
0.8	
0.9	
1.0	100 % Probability of Losses - Total Loss

Figure 45. Key to Influences of Risk on Model Elements

slightly decrease. Figure 46 illustrates the risk realized in each zone. In the exclusion zone, closest to the volcano, risk is realized at 100%, while in zone 3 (furthest from the volcano) the realized risk is 70% of the actual risk realized in the exclusion zone.

5.4.2 Risk Models

Figure 47 illustrates the actual and perceived risk portion of the model as it is depicted by the Powersim system dynamics modeling software. The key state variable is ARISK or actual risk. Actual risk is a value that corresponds with risk values in Figure 45. The value is aggregated and it is defined by levels of volcanic activity as they relate to a realized risk. In addition to rate controls, which are set to mathematically simulate various types of volcanic risk scenarios, a step function is added to simulate a situation where volcanic activity increases at a quicker rate, simulating a more intense period of volcanic activity with rapidly increasing risk levels. PRISK or perceived risk is a function of actual risk, however a first order information delay is added. As it takes time to perceive the risk, there is a delay in when the actual risk will be perceived. This delay is reflected as a smooth in the risk rate. In the larger model, risk perception acts to decrease the rate of in-migration to the island.

Figure 48 illustrates the model for risk as realized by zone as depicted by the Powersim system dynamics modeling software. The state variable RISKREDCAP is risk reduction capacity and it represents the ability to reduce risk in each zone. Activities such as hazard mitigation, increased preparedness, and pre-disaster planning can reduce risk within certain limits. The model is designed to reflect a policy of increasing the risk reduction capacity to the highest level possible in zone 3, to a lesser extent in zone 2, and to the least extent in zone 1. As zone 3 has both the least risk and the most population, a

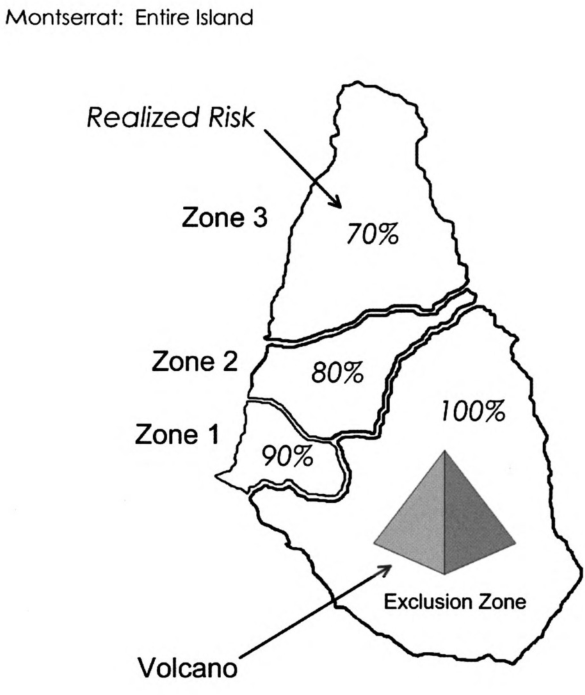


Figure 46. Realized Risk by Montserrat Geographic Zones

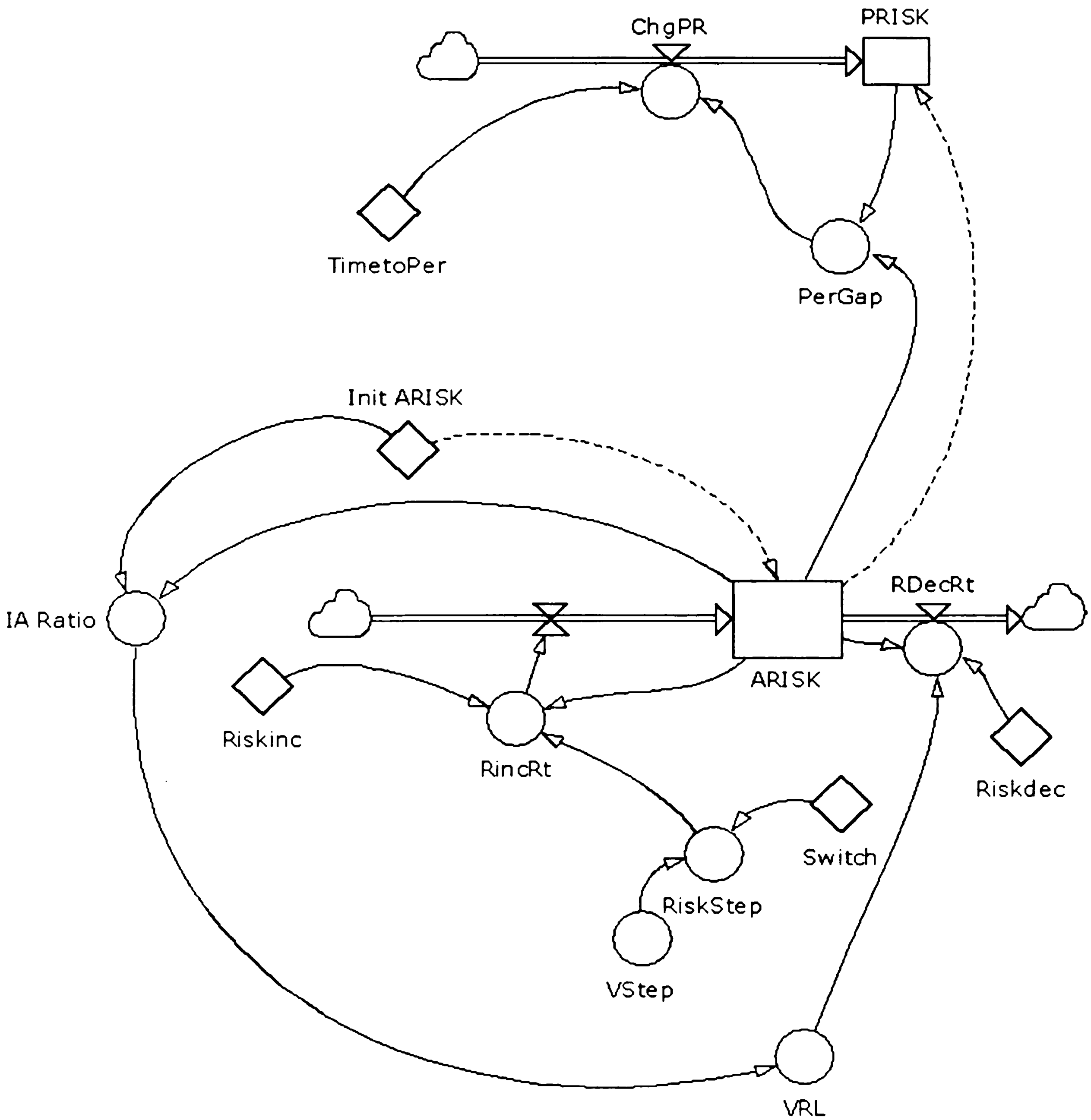


Figure 47. Actual and Perceived Risk Sector of Model

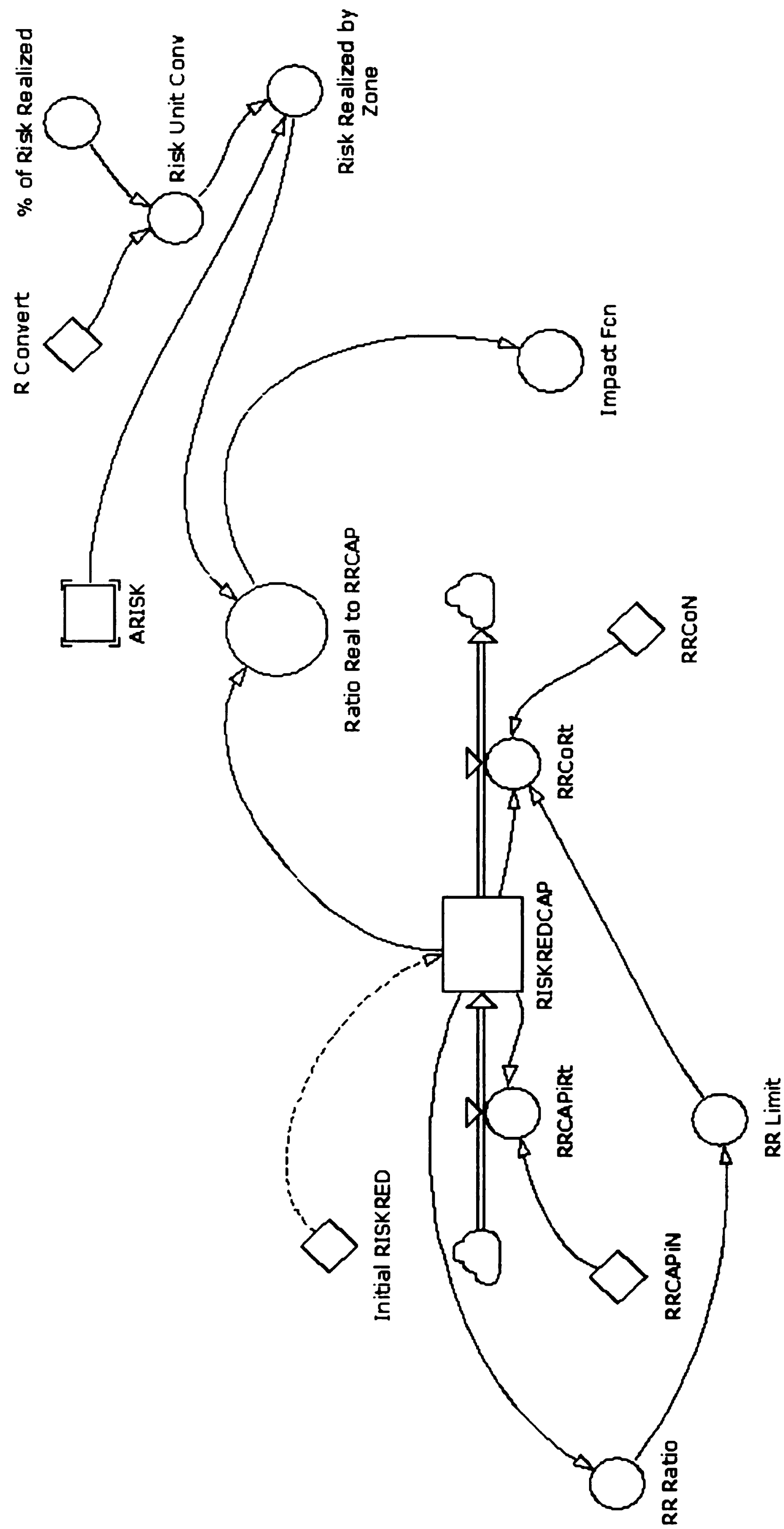


Figure 48. Model for Risk as Realized by Zone

policy to increase risk reduction the most in zone 3 would have the greatest impact in increasing the island's population. The risk reduction capacity can only increase to a specific level because it is limited by the amount of financial resources, equipment, and manpower that is available for such activities. Risk reduction capacity acts through the impact function multiplier to influence the construction rate. Figure 49 illustrates the interactions of actual risk and risk reduction. In the situation where the risk reduction capacity is greater than the actual risk, it results in the impact multiplier having a value greater than one, which in the model would act to increase the construction rate. In considering risk by zone, it should be noted that the actual risk realized is also moderated by the distance of the location being modeled from the volcano (see Figure 46).

5.5 The Montserrat Urban and Risk Model

Figure 50 provides a stylized representation of the Montserrat Urban and Risk Model applied in this study. The actual risk model (see Figure 47) replicates the risk of the volcano and that risk value (based on the concept of risk in Figure 45) is fed into the risk model for each zone (see Figure 48). The perceived risk model (see Figure 47) is a first order information delay function that can act to reduce the level of in-migration to each zone. Risk then effects the zone 1 urban model, the zone 2 urban model, and the zone 3 urban model. Risk acts on the model by influencing the in-migration to each zone through perception, influencing the construction rate of homes and business structures, influencing the rate of movement between zones, and when the risk level surpasses the threshold level of 0.6. the action of risk can destroy homes, destroy business structures, reduce the land fraction occupied (by making land unsuitable for future development),

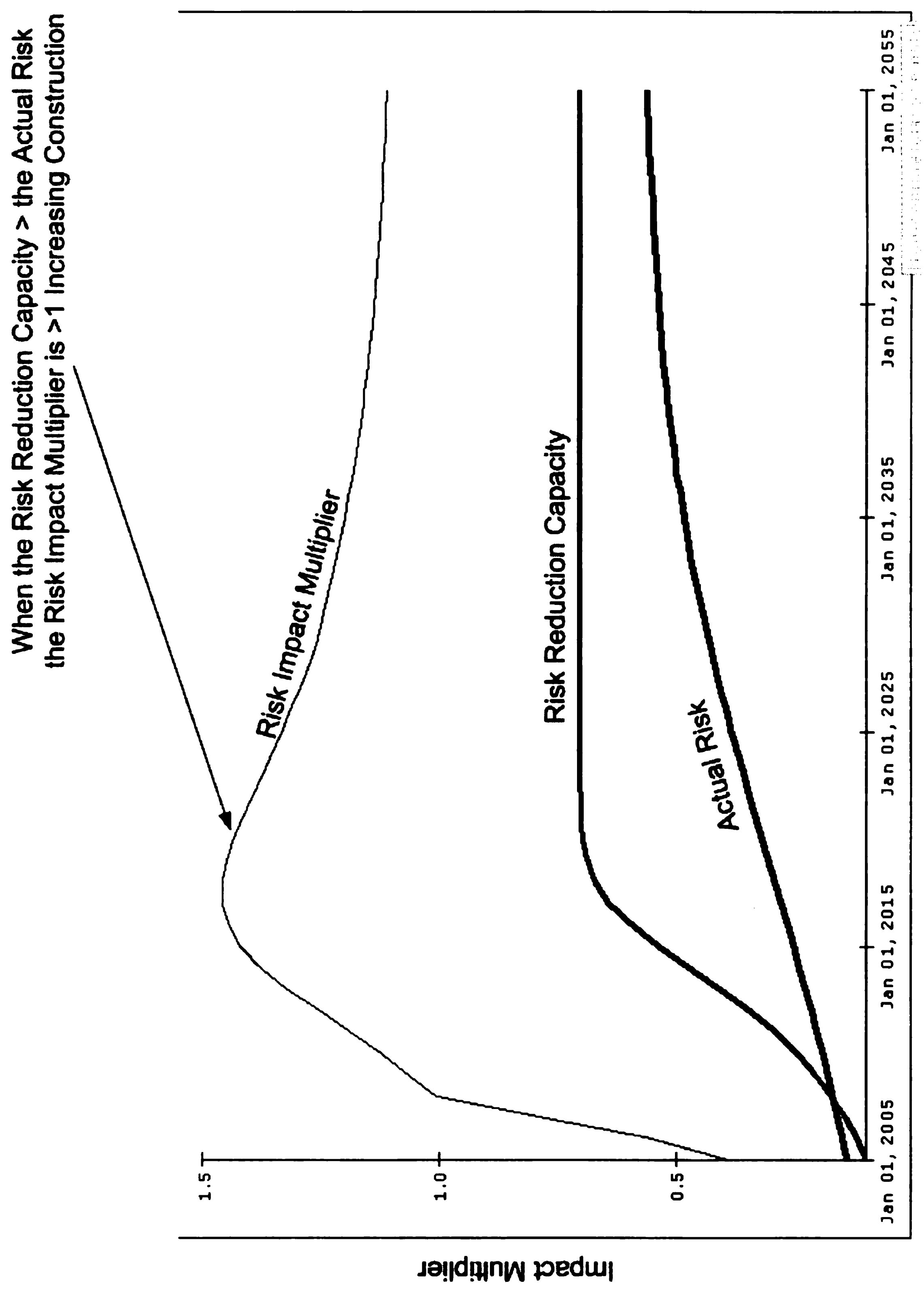


Figure 49. Interactions of Actual Risk and Risk Reduction Capacity
(Non-Commercial Use Only)

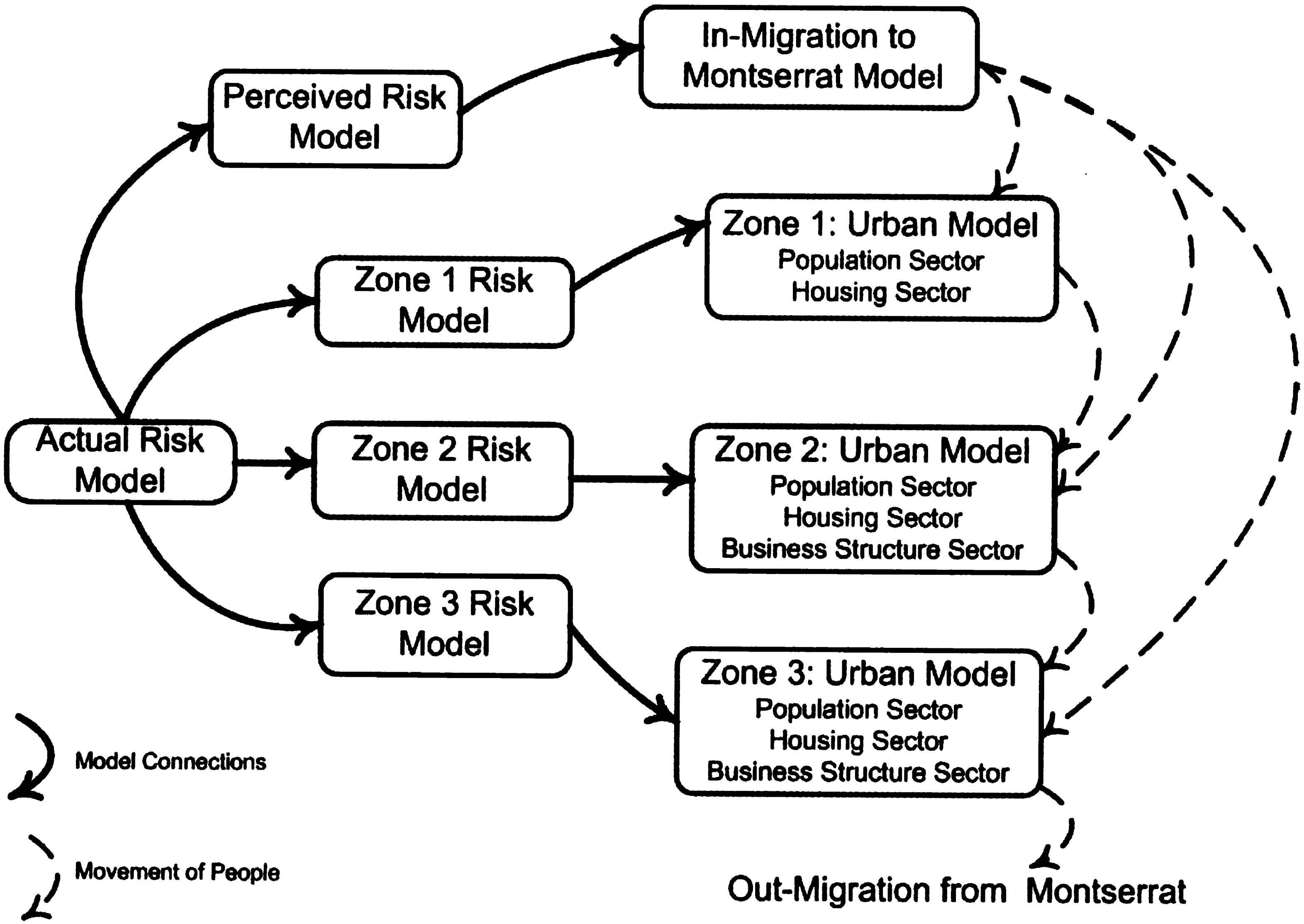


Figure 50. Stylized Representation of the Montserrat Urban and Risk Model

and cause the population to flee to zones of lesser risk. As risk increases in zone 1, zone 2, and zone 3 conditions decline and population can be pushed off the island. While Figure 50 provides a stylized representation of the model, the Appendix 1 provides a more detailed description of the model components with depictions of the system dynamics model from the Powersim computer software and definitions of the variables used in the model.

This is to certify that the
dissertation entitled

Taking A Systems Approach to Risk Assessment and
Disaster Recovery: The Case of Montserrat

presented by

Jack Lewis Rozdilsky

has been accepted towards fulfillment
of the requirements for the

Doctoral degree in Resource Development - Urban Studies

G. Schultink

Major Professor's Signature

June 7, 2005

Date

Doctoral Dissertation

TAKING A SYSTEMS APPROACH TO RISK ASSESSMENT AND DISASTER RECOVERY: THE MONTSERRAT CASE

VOLUME II

By

Jack Lewis Rozdilsky

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Resource Development and Urban Studies

2005

CHAPTER SIX

THE MONSERRAT URBAN AND RISK MODEL: SIMULATION AND OUTPUT FROM FOUR RISK SCENARIOS

6.1 Simulation of Risk Conditions with Four Scenarios

This chapter concerns the presentation of the output from the Montserrat Urban and Risk Model. The results from four the scenarios are presented. The key difference in each of the scenarios is the level of risk faced. *SCENARIO A* is a base scenario that can be compared to the other three scenarios that have a variation in the risk levels. *SCENARIO A* establishes conditions where Montserrat reaches its stated development goal of 10,000 persons during the next 50 years. When comparing the output from *SCENARIO B*, *SCENARIO C*, and *SCENARIO D* to the output from *SCENARIO A*, it is important to keep in mind the purpose of the model. The model is intended to provide insight concerning the question: "Is the post-disaster redevelopment goal of reaching a population of 10,000 persons feasible, given a situation of development constraints and continued risks?"

Before presenting the model's output, model testing is discussed. Model testing provides the modeler with the opportunity to test the model's robustness. In addition, to model testing an appropriate time frame for the model needs to be established. This chapter also provides a discussion of why the time frame of 50 years was chosen for the simulations.

In terms of output from the model, a series of sixteen graphs and their associated tables is presented. Following the discussions of model testing and temporal aspects of the model, a description of model's output is provided. In conclusion, the four scenarios are presented. The four scenarios simulated using the Montserrat Urban and Risk Model are:

1. *SCENARIO A* – Base Simulation with Low Risk
2. *SCENARIO B* – Medium Risk
3. *SCENARIO C* - Medium Risk with Step
4. *SCENARIO D* - High Risk

Each scenario is described, sixteen aspects of the model's output are presented in graphical form, and then initial comments on the results are provided. A full discussion of the analytical results is provided in next chapter, Chapter Seven.

6.2 Simulation Aspects - Model Testing

Before considering the output from the model, this author would be remiss in not discussing the testing of the model. All models are simplified representations of the real world. Inherent in that representation, many subjective assumptions are made by the modeler. Through sensitivity testing, the relationships of the variables being modeled can be tested under various circumstances to see if the model's behavior is consistent with interactions in the real world.

Various types of sensitivity testing can be applied to test for robustness. The Montserrat Urban and Risk Model was tested under various conditions before the results presented later in this chapter were generated. Model testing starts with creation of the first equation. While the model was constructed, each segment was first tested on its own and then as segments of the model were interconnected by various multipliers, the multipliers were switched to a value of one to isolate feedback loops and check behavior.

Specifically sensitivity testing considerations along with structural assessment, dimensional consistency, parameter assessment, and extreme conditions were applied. In structural assessment, various values were tested to see if the model conformed to basic physical laws. For example, a decreasing rate of construction of houses combined with a constant rate of demolition of houses should result in a lower number of houses. In this case, if the output from the state variable of houses showed otherwise, there would be a violation of the physical laws of material flow. For dimensional consistency, the modeling software was used to inspect all of the equations for suspect parameters. For the model to function properly, all the units for each variable had to be consistent. In testing extreme conditions, high and low values were provided for model input and the output from each equation was inspected to test the model's responses to various values. The behavior of the model should be consistent, for example, when high risk values establish conditions that cause out-migration of population from one zone, in-migration should be picked up by another zone. In all, the sensitivity analysis tests whether the model shows reasonable behaviors, when the values related to the assumptions are varied over a plausible range of uncertainty.

Despite the limitations inherent in system dynamics modeling, the Montserrat Urban and Risk Model was tested and this author concluded that the level of aggregation in the model is consistent with the purpose of this study's modeling effort. In addition, Chapter Five and the appendix provide documentation of the model so that further study and refinement of this model can take place.

6.3 Simulation Aspects - Temporal Aspects of the Simulation

A time period of 50 years was selected as the appropriate time frame for the simulation of the Montserrat Urban and Risk Model. Time frames for urban planning, volcanic activity, and other system dynamic models were considered. To make the model relevant, it was necessary to balance both the shorter-term considerations of physical planning requirements and longer-term processes of volcanic activity.

The current Montserrat physical development plan has been designed to establish planning goals for a ten-year period (1998-2008). In urban planning, typical time periods for plans can range from longer-term 10 to 25 year plans to shorter-term plans covering a period of one to five years. Plans such as a long-range transportation plan or a city's comprehensive plan are usually developed for 25 years into the future and are updated on five to ten year cycles. Such plans are designed to establish goals for longer-range development and usually some, but not all, of the visions in the plan are implemented. The Montserrat Physical Development Plan 1999-2008 is an example of such a longer-range plan. The document dated 1999 states:

> "Nearly two thirds of the island is now considered unsafe and a large proportion of property and infrastructure has been lost. Under these conditions physical planning has necessarily been reactive and decisions had been made in response to urgent needs in a crisis situation. The purpose of this document is to facilitate planning on a proactive basis. Its aim is to give guidance to and direction to the government, the private sector, NGO's and the community, and to provide a basis for the coordination and integration of development activities" (Physical Planning Unit, 1999).

Shorter-term plans such as local area plans or pre-disaster plans are typically developed on a one to five year basis. These plans are designed to guide implementation activities in the immediate-term. An example of a shorter-term plan is the hazard mitigation plans being developed in the United States under the Disaster Mitigation Act of 2000. These plans both assess current conditions as related to natural, technological, and social hazards and suggest short-term proactive planning activities to reduce disaster risk. (Rozdilsky, 2002).

In considering the Montserrat case, the temporal activity of the volcanic hazard also must be taken into consideration. The active life span of a most volcanoes has been estimated to be between one and two million years. If a volcano has erupted during historic times it should be regarded as active. To date, no volcano has revealed a recognizable cycle of activity that has could be used to predict the time of eruptions. In a few cases, prediction of volcanic activity can be made to an accuracy of decades (Bell, 1999). Clearly, a difficulty is presented since what is considered to be the very long-term for urban planning-type activities is the very short-term in terms of volcanic activity. As a volcano operates on geologic time scales, even a human lifetime or spans of generations can be considered as an inconsequential time period in terms of volcano's time span of activity. Therefore, unlike some other hazards of shorter duration, volcanic hazards represent special difficulties when planning to deal with their consequences.

For final considerations of temporal aspects of the model, a review of other system dynamic models took place. Forrester's original urban models were designed to simulate the life-cycles or urban areas during time periods ranging from 50 to 250 years (Forrester, 1969). In Forrester's industrial dynamics models, business cycles were typically modeled over 100 to 350 years (Forrester, 1961). Meadow's world models depicting global population and resources changes depicted 100 to 200 year time frames (Meadows & Club of Rome., 1972) .

All things considered, 50 years was chosen as a compromise between a relevant urban planning time frame and a volcanic activity frame. In addition, in the survey of other applications of urban dynamic modeling efforts, 50 years was a reasonable time frame in which interactions between dynamic behaviors can be illustrated.

6.4 Explanation of the Depiction of the Model Output

Output from the four scenarios is depicted in a consistent fashion of 16 graphs for each scenario.

On all of the graphs, the x-axis is labeled as time. The time frame is starts with the initial time of January 1, 2005 and ends final time of January 1, 2055.

The y-axis represents a value related to the behavior of the variable being examined. The minimum / maximum values are set to be uniform across the scenarios to allow for cross-scenario comparisons.

A total of 16 aspects of model behavior are presented for each scenario as follows:

- Graph #1 depicts the total population of the island. The unit is people. For example, for *SCENARIO A*, this graph would be labeled A1 and for *SCENARIO B*, this graph would be labeled B2, etc.
- Graph #2 depicts the population of each zone on the island. The total sum of the population from each zone is depicted in Graph #1. The unit is people.
- Graph #3 depicts the total number of houses on the island. The unit is houses.

- Graph #4 depicts the number of houses in each zone of the island. The total sum of the houses from each zone is depicted in Graph #3. The unit is houses.
- Graph #5 depicts the total number of business structures on the island. The unit is business structures.
- Graph #6 depicts the number of business structures in each zone of the island. The total sum of the business structures from each zone is depicted in Graph #5. The unit is business structures.
- Graph #7 depicts the total number of jobs on the island. The unit is jobs.
- Graph #8 depicts the number of jobs in each zone of the island. The total sum of jobs from each zone is depicted in Graph #7. The unit is jobs.
- Graph #9 depicts both the actual risk and the perceived risk. As risk is a function of location on the island, this risk would specifically represent the risk in zone 0, or the exclusion zone. Risk perception is based on the actual risk. When referring to risk on island in general, the actual risk is used. The unit is risk units.
- Graph #10 depicts the risk as realized in each zone. As risk is related to location, 90% of the actual risk is experienced in zone 1 (closest to the volcano), 80% of the actual risk is experienced in zone 2, and 70% of the risk is experienced in zone 3 furthest from the volcano. The unit is risk units.
- Graph #11 depicts the total land fraction occupied on the island. For example, a value of 0.4 would indicate that 2/5 of the island's land is occupied and 3/5 remains open for future occupation. As the land fraction occupied approaches 1.0, less land is available. The unit is a fraction ranging from zero to one.

- Graph #12 depicts land fraction occupied by individual zone. Graph #11 depicts the sum of the land fraction occupied for all three zones. The unit is a fraction ranging from zero to one.
- Graph #13 depicts the in-migration rate from overseas. This in-migration is then distributed across the three zones with 10% going to zone 1, 20% going to zone 2, and 70% going to zone 3. The unit is people per year.
- Graph #14 is the off-migration rate of people from the island to locations overseas. According to parameters established in the model, this off migration originates from zone 3. The unit is people per year.
- Graph #15 is the rate of population movement from zone 1 to zone 2. This value serves as a part of the input to the in-migration to zone 2. The unit is people per year.
- Graph #16 is the rate of population movement from zone 2 to zone 3. This value serves as a part of the in-migration to zone 3. The unit is people per year.

Appendix 4 and Appendix 5 also augment the data presented in this chapter. Appendix 4 provides the population tables for each scenario. Data from Graph #1 and Graph #2 are depicted in tabular form. Appendix 5 provides the land fraction occupied tables for each scenario. Data from Graph #11 and Graph #12 are depicted in tabular form. Both population and land fraction occupied were chosen to be depicted in the appendices in tabular form since they provide key results relevant to the interpretations.

6.5 Presentation of the Scenarios

In this study, four scenarios are both simulated and analyzed. This section will describe the scenarios, present the 16 graphs generated from running the model under conditions established in each of the scenarios, and then provide initial comments on the output. Chapter 7 will then provide a more thorough discussion of the analytical results.

6.5.1 *SCENARIO A* – Base Simulation with Low Risk

SCENARIO A is named the base simulation with low risk.

In the base scenario, risk is kept constant (Figure 59). The base scenario is important since it illustrates the functioning behavior of the Montserrat Urban and Risk Model, without influences of risk. While this scenario is unlikely, as risk from the volcano will increase over time, the scenario is useful to serve as a base model for comparison with the other scenarios. In considering future sustainability of the island's urban systems on their own, this base model can be used to experiment with different development scenarios.

The values used in the model were chosen to achieve the established goal of reaching a population of 10,000 people. While the population growth rate could have been set faster, considering the situation on Montserrat, it is suggested that a slower phased build-up of population would be more likely to occur given the physical, material, and spatial limits on the island.

Starting with the initial population (as described in chapter 2) of 4,690 persons, in this scenario the population grows gradually to 10,000 persons over the 50 year period. Housing, business structures, jobs, and land fraction occupied all respond to the level of the population. The initial values of the base scenario will be kept constant throughout the simulations so that when the risk level is changed, a comparison can be made concerning how risk impacts the development goal of reaching 10,000 persons.

6.5.1.1 *SCENARIO A* – Model Output

The following Figures 51-66 depict the results of *SCENARIO A*.

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A1

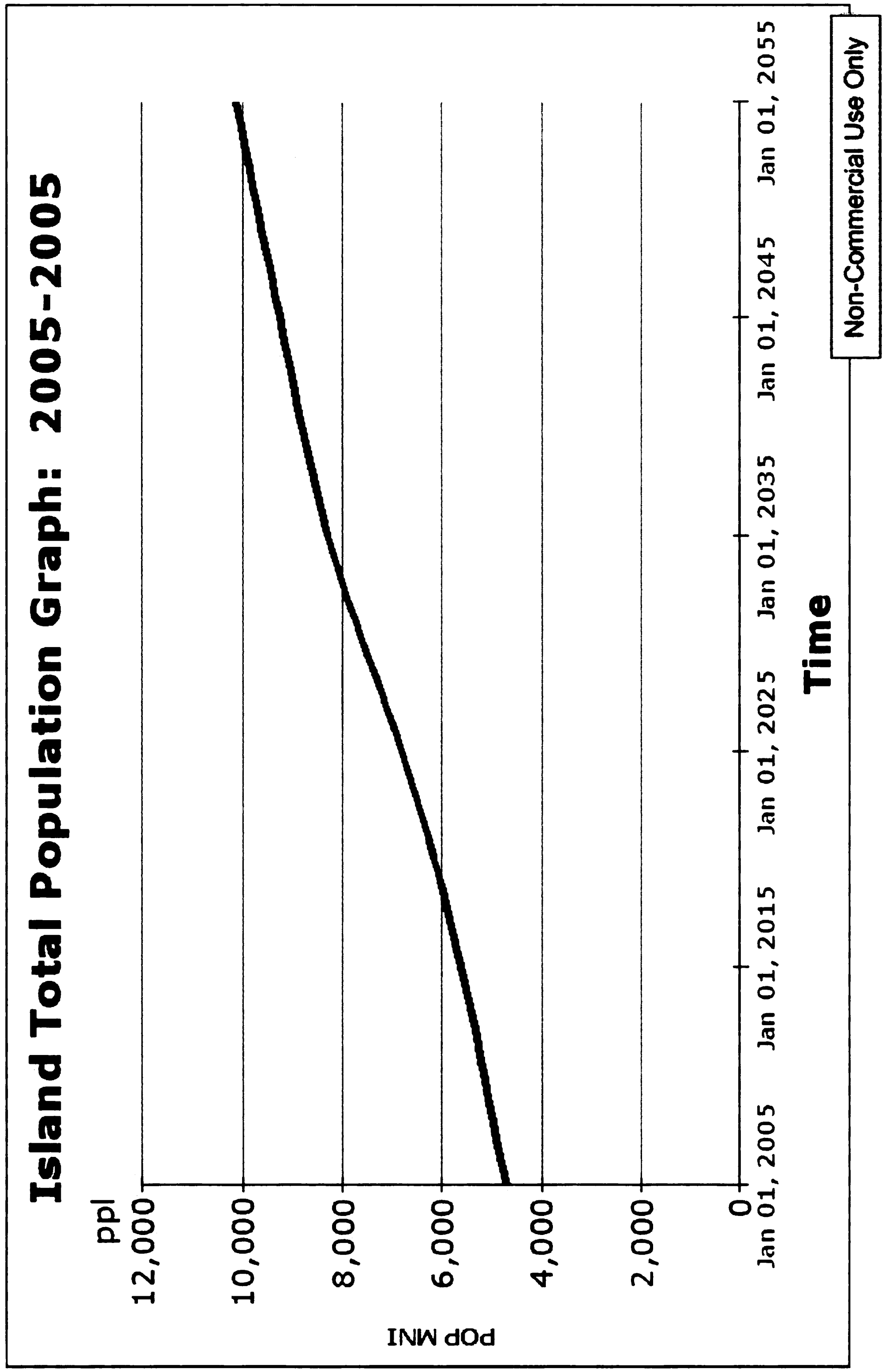


Figure 51. Model Output Graph A1

Montserrat Urban and Risk Model: Output Scenario A: Base Scenario with Low Risk Graph A2

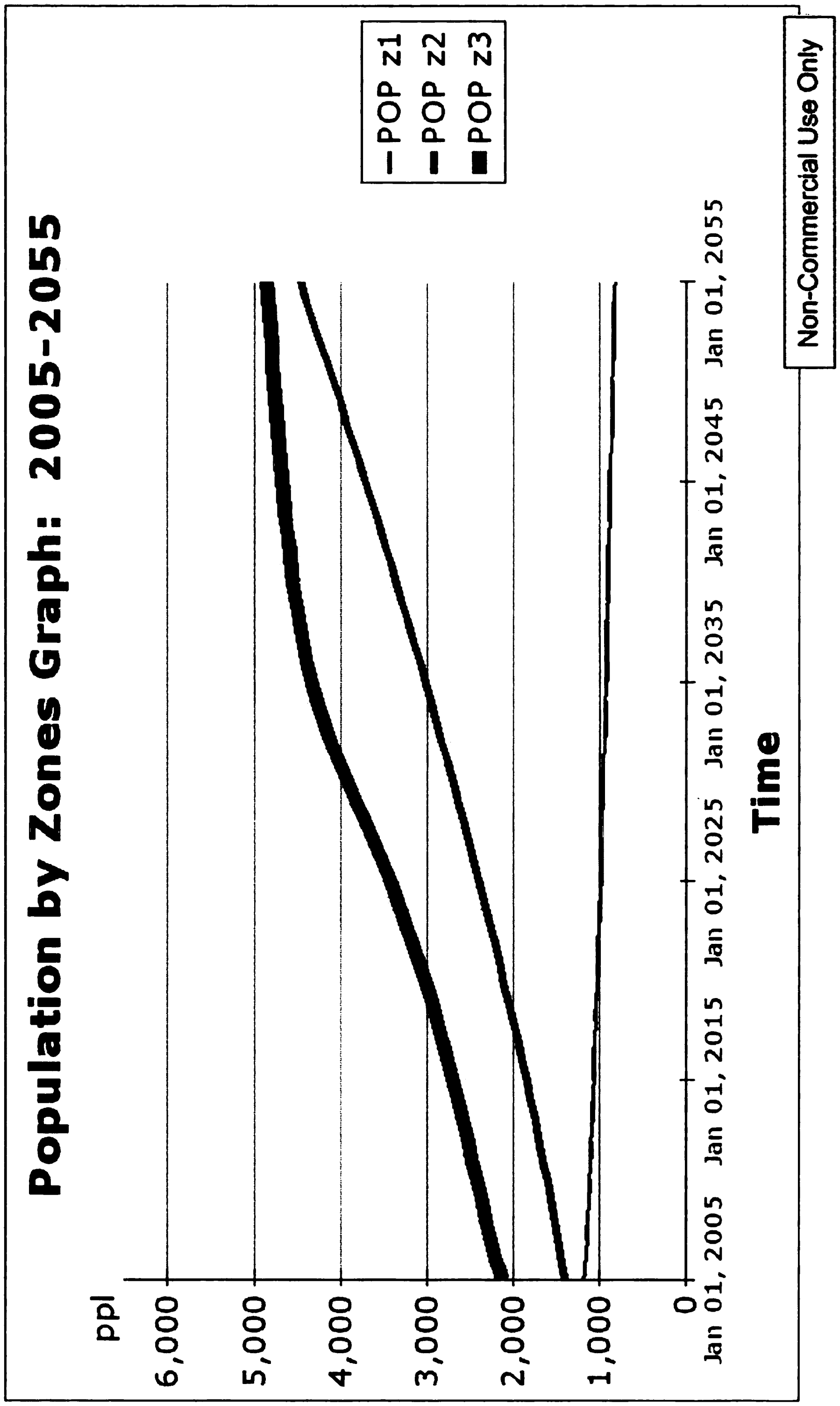


Figure 52. Model Output Graph A2

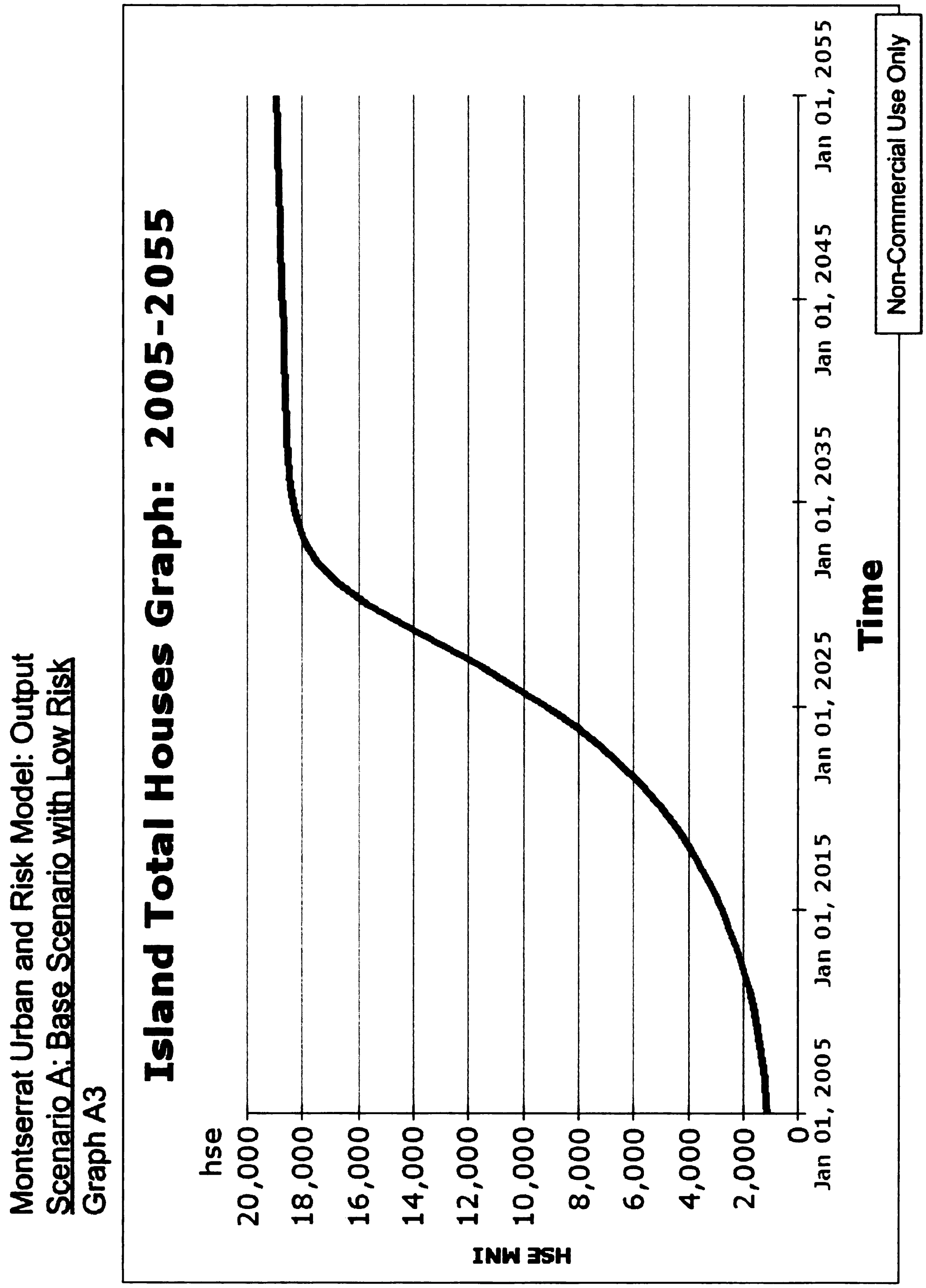


Figure 53. Model Output Graph A3

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A4

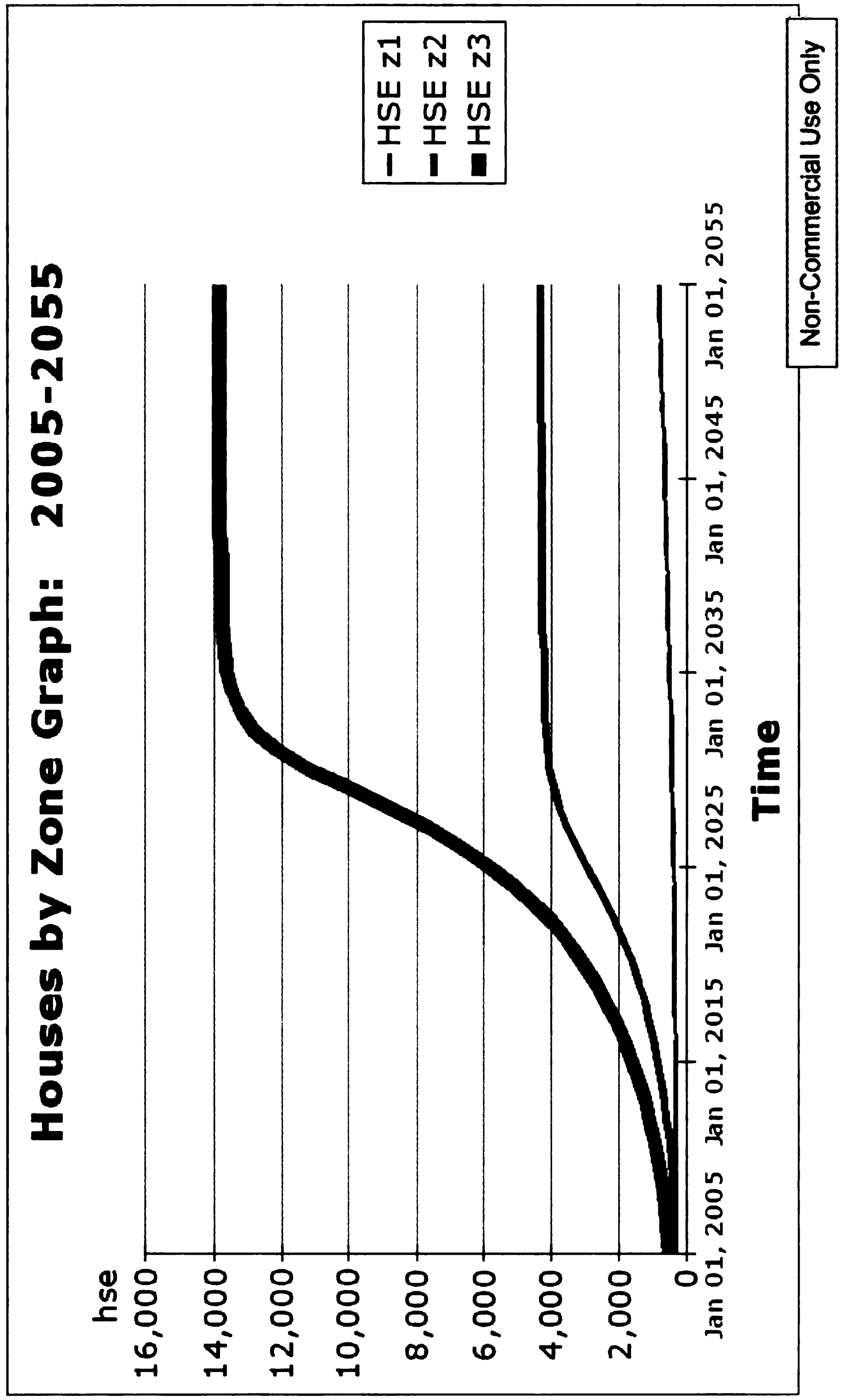


Figure 54. Model Output Graph A4

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A5

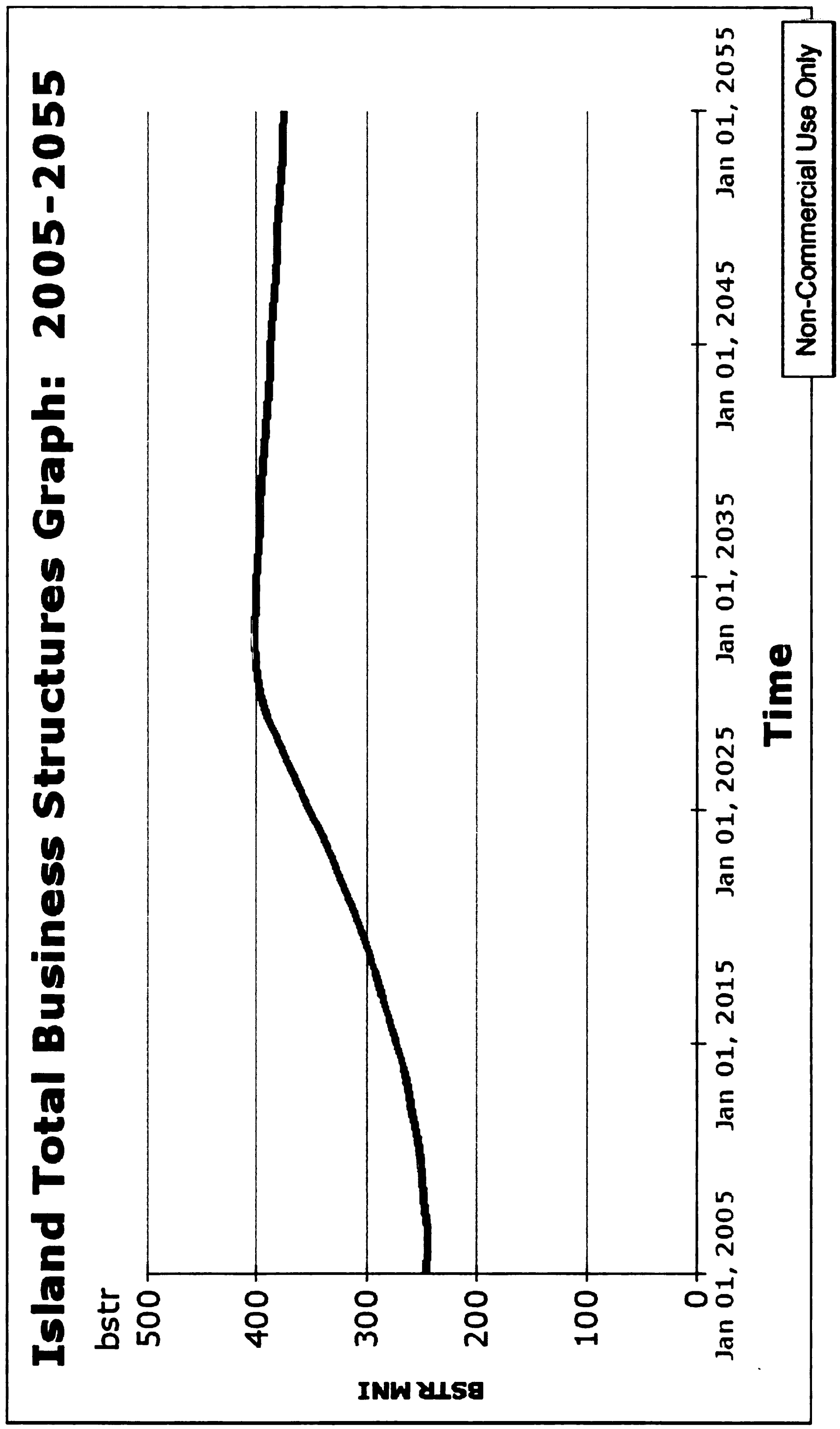


Figure 55. Model Output Graph A5

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A6

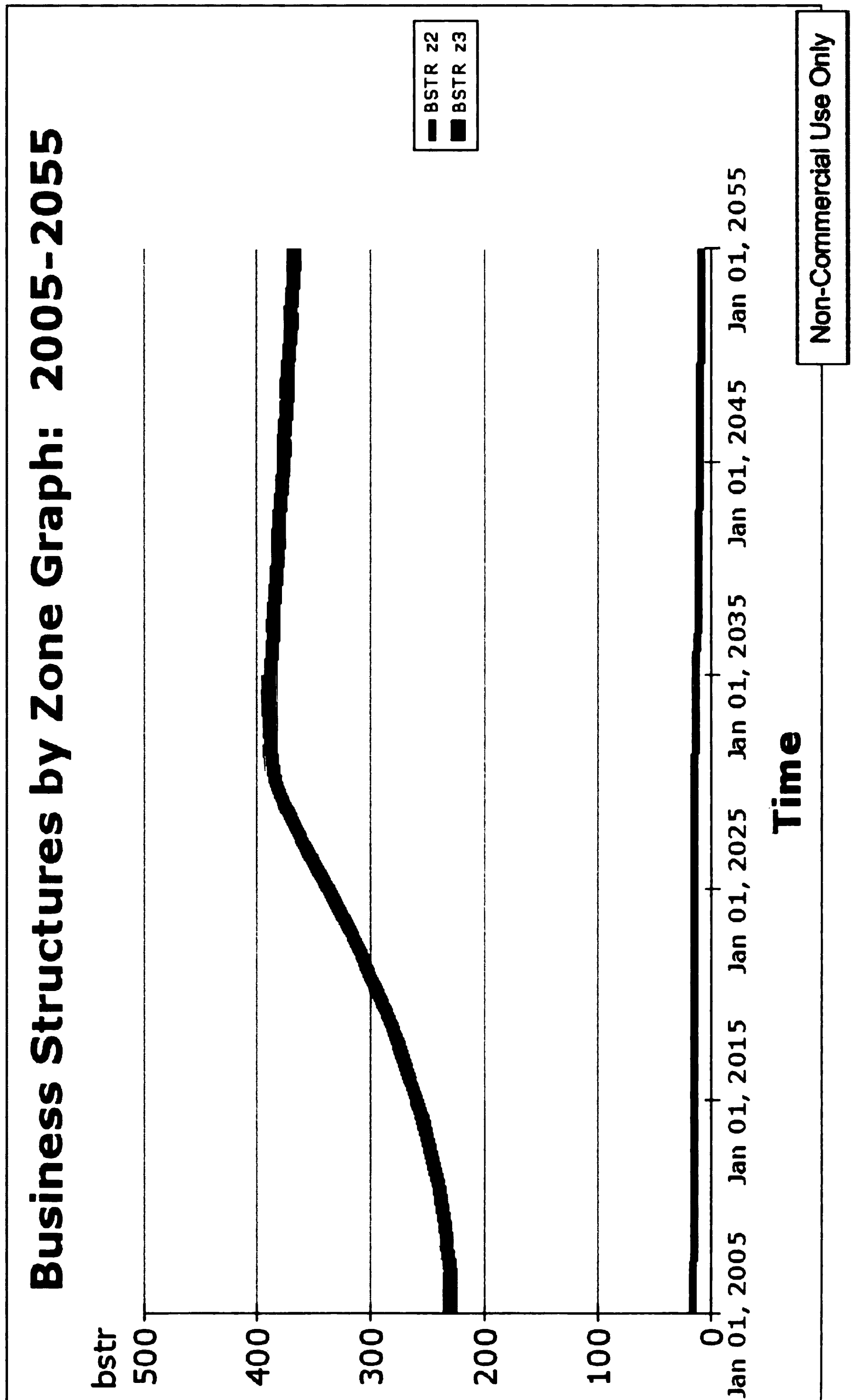


Figure 56. Model Output Graph A6

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A7

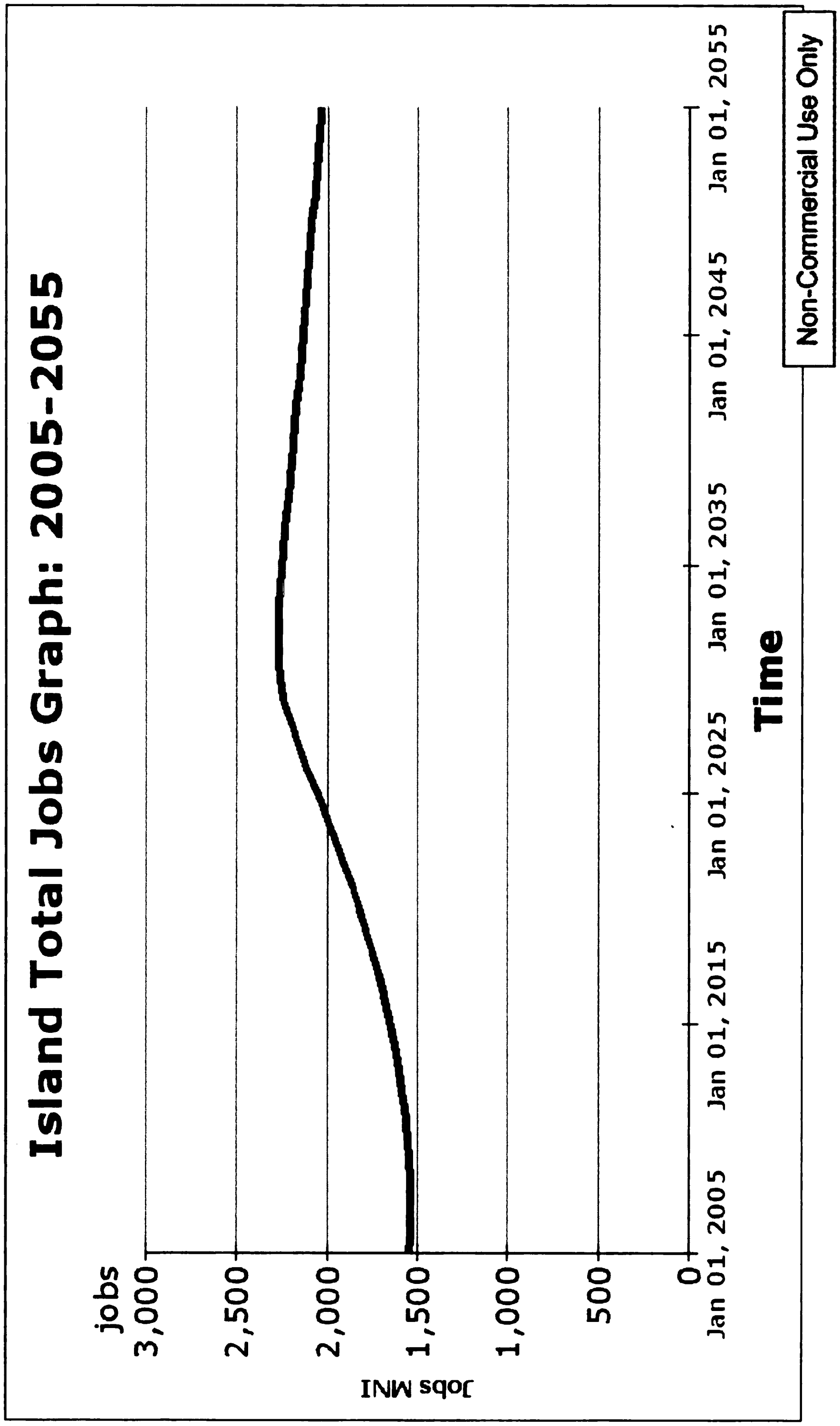


Figure 57. . Model Output Graph A7

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A8

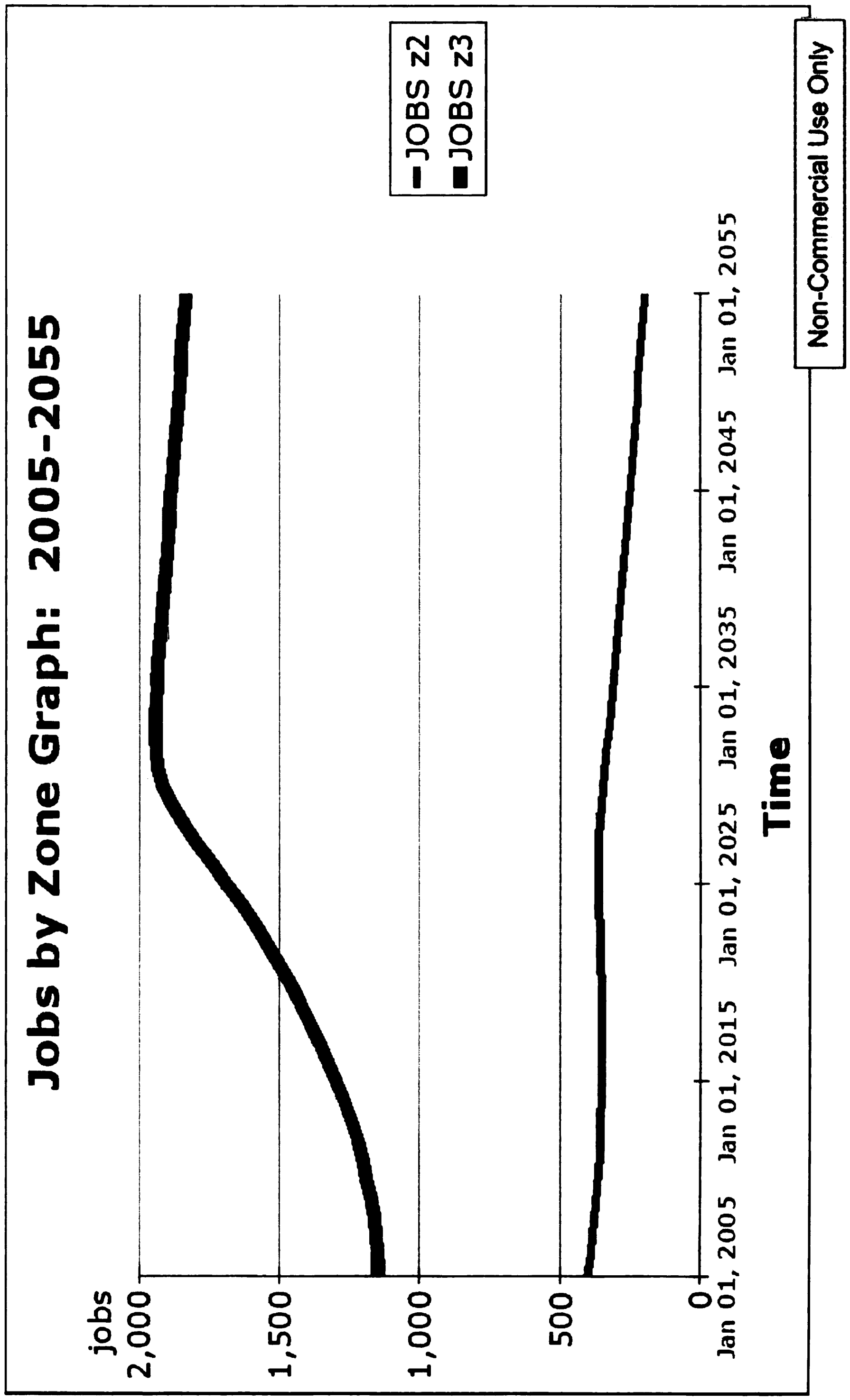


Figure 58. Model Output Graph A8

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A9

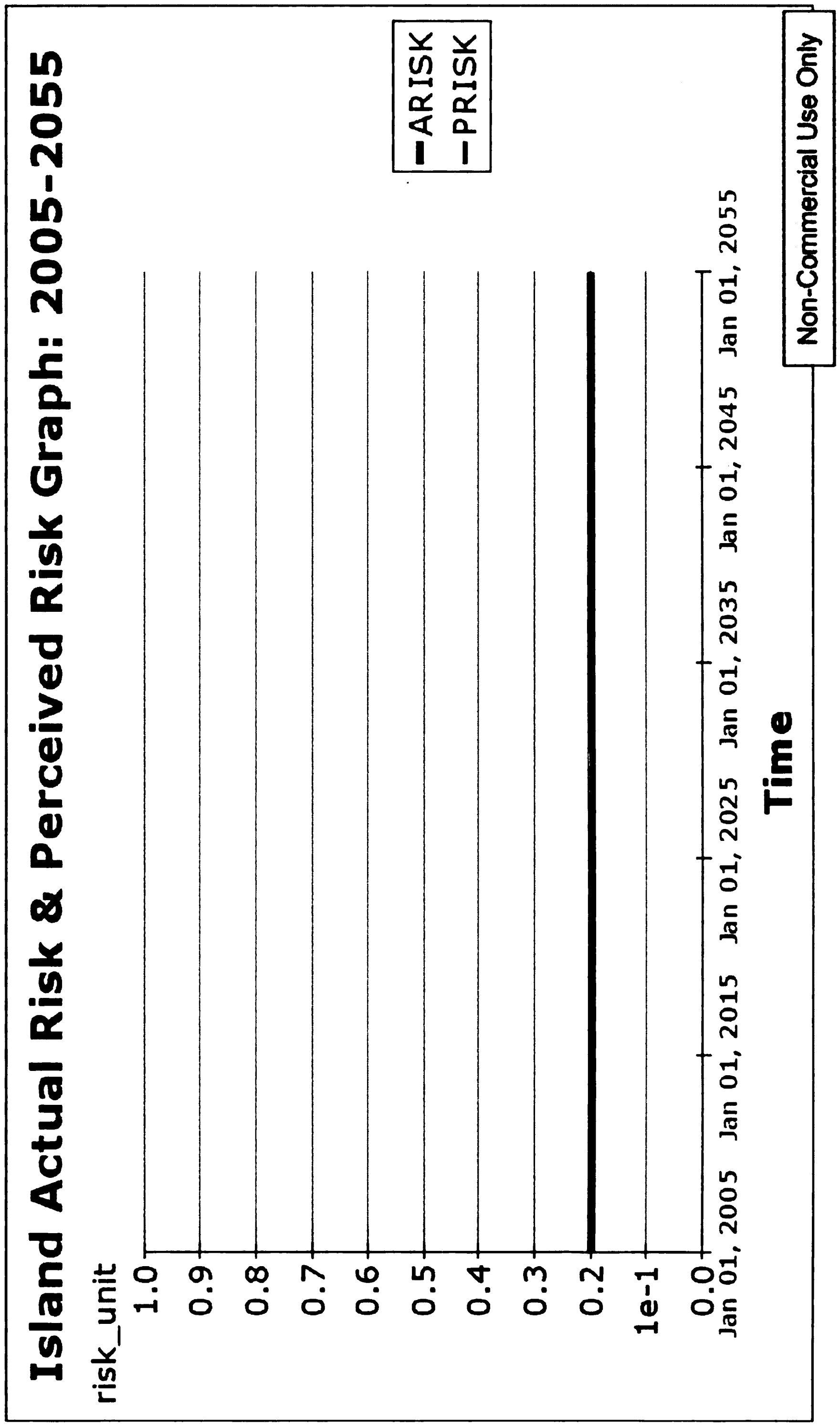


Figure 59. Model Output Graph A9

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A10

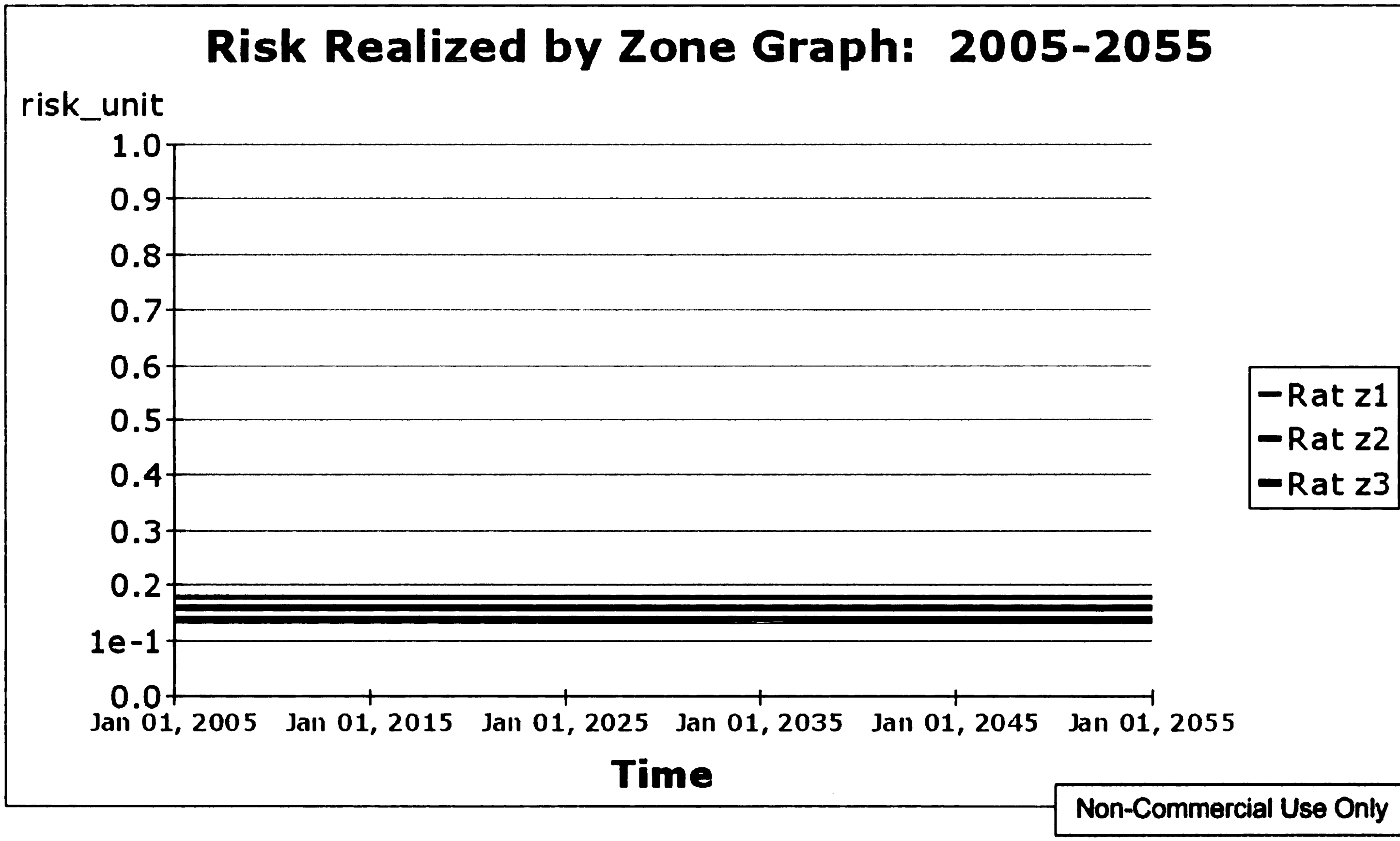


Figure 60. Model Output Graph A10

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A11

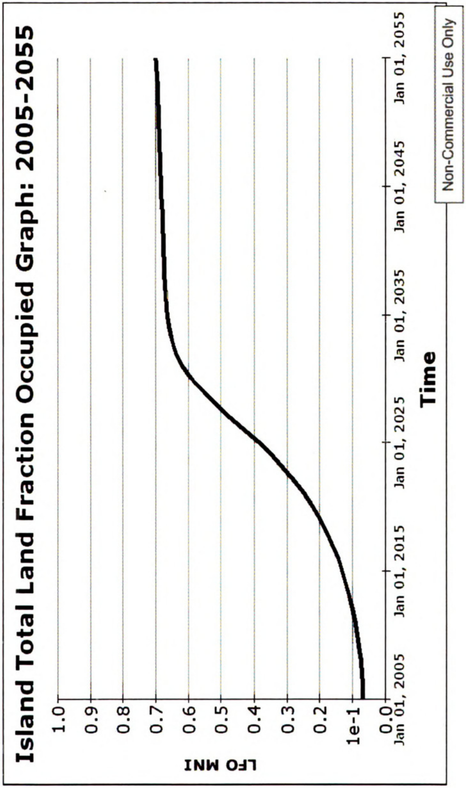


Figure 61. Model Output Graph A11

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A12

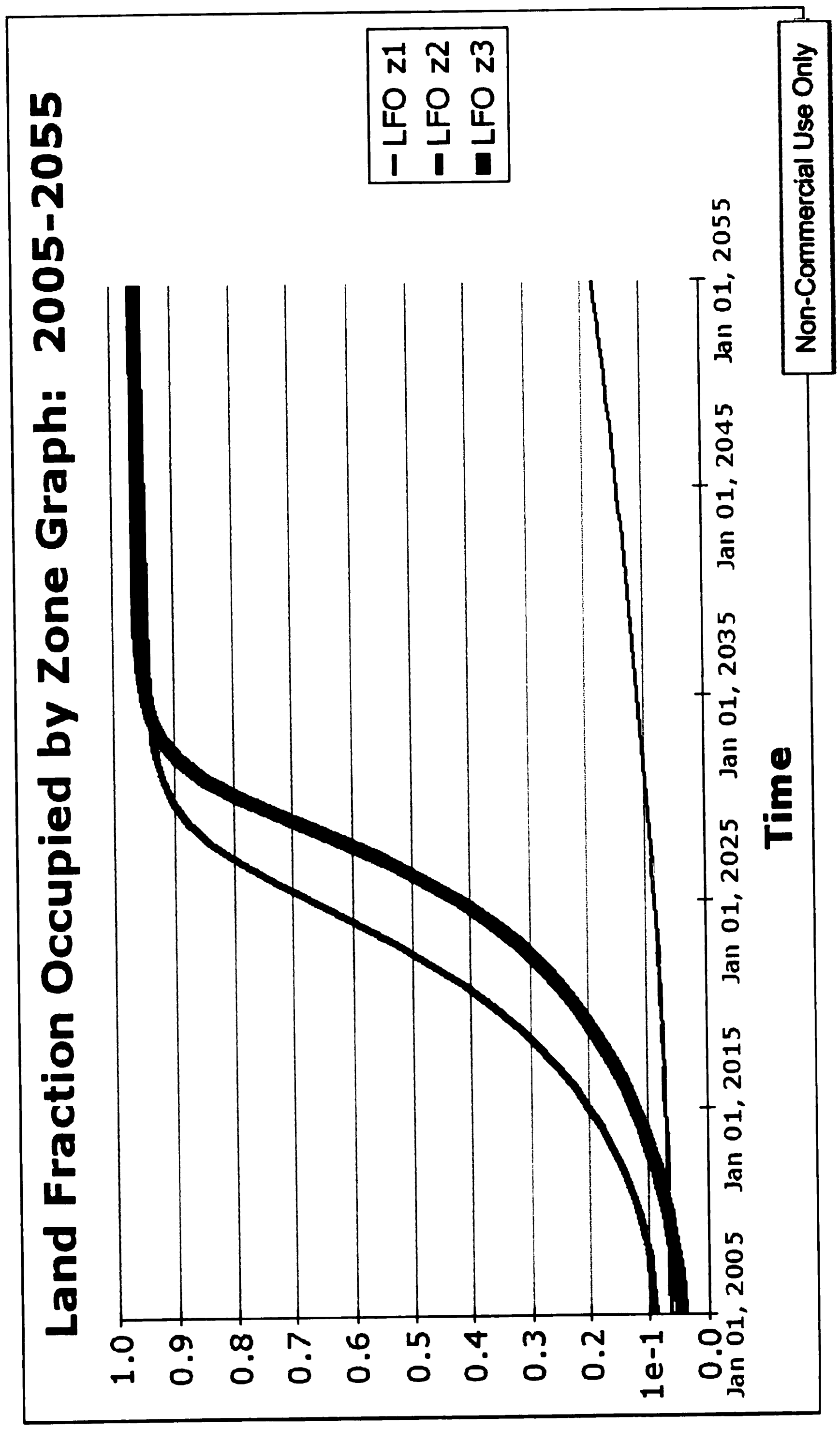


Figure 62. Model Output Graph A12

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A13

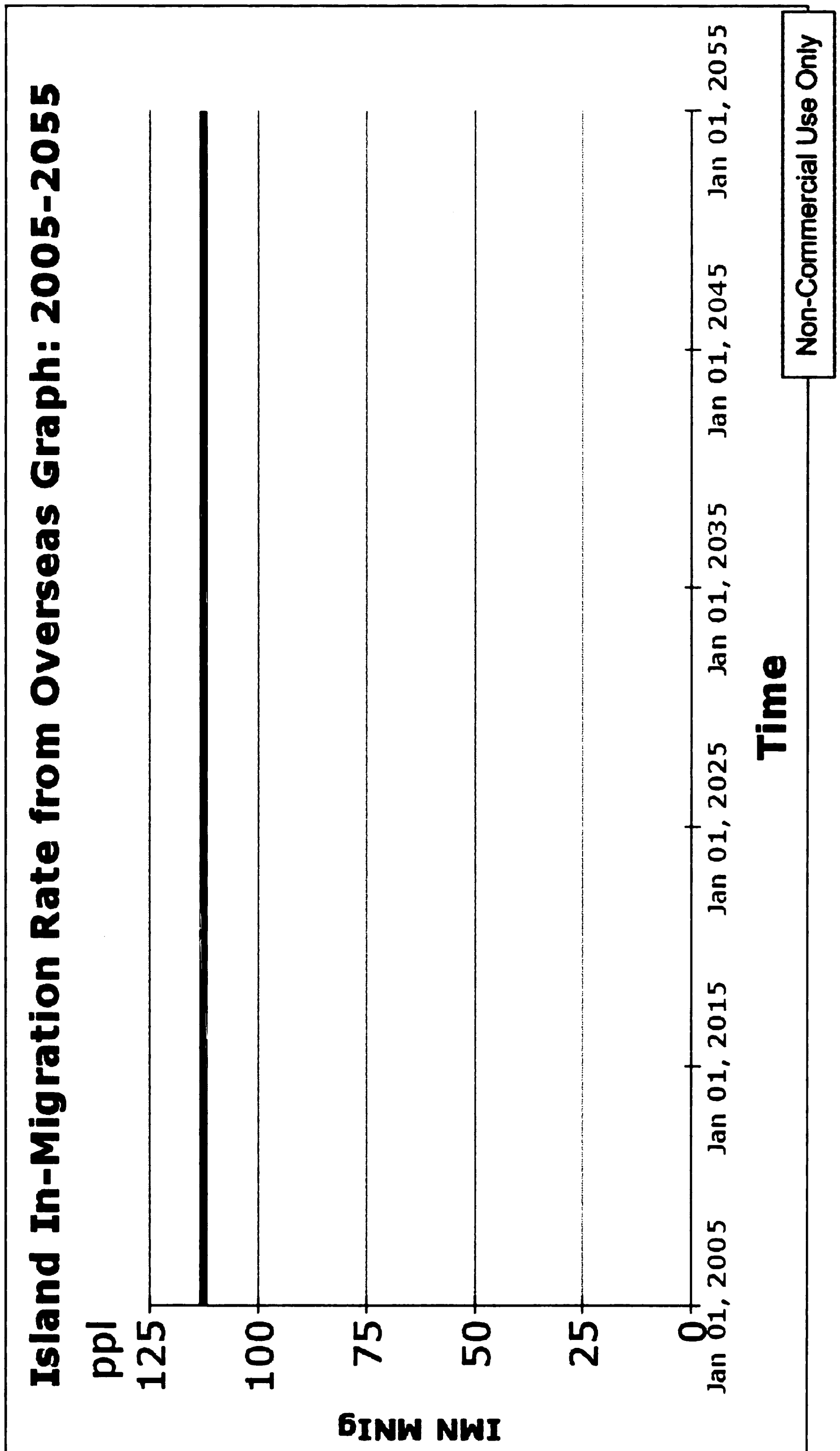


Figure 63. Model Output Graph A13

Montserrat Urban and Risk Model: Output Scenario A: Base Scenario with Low Risk Graph A14

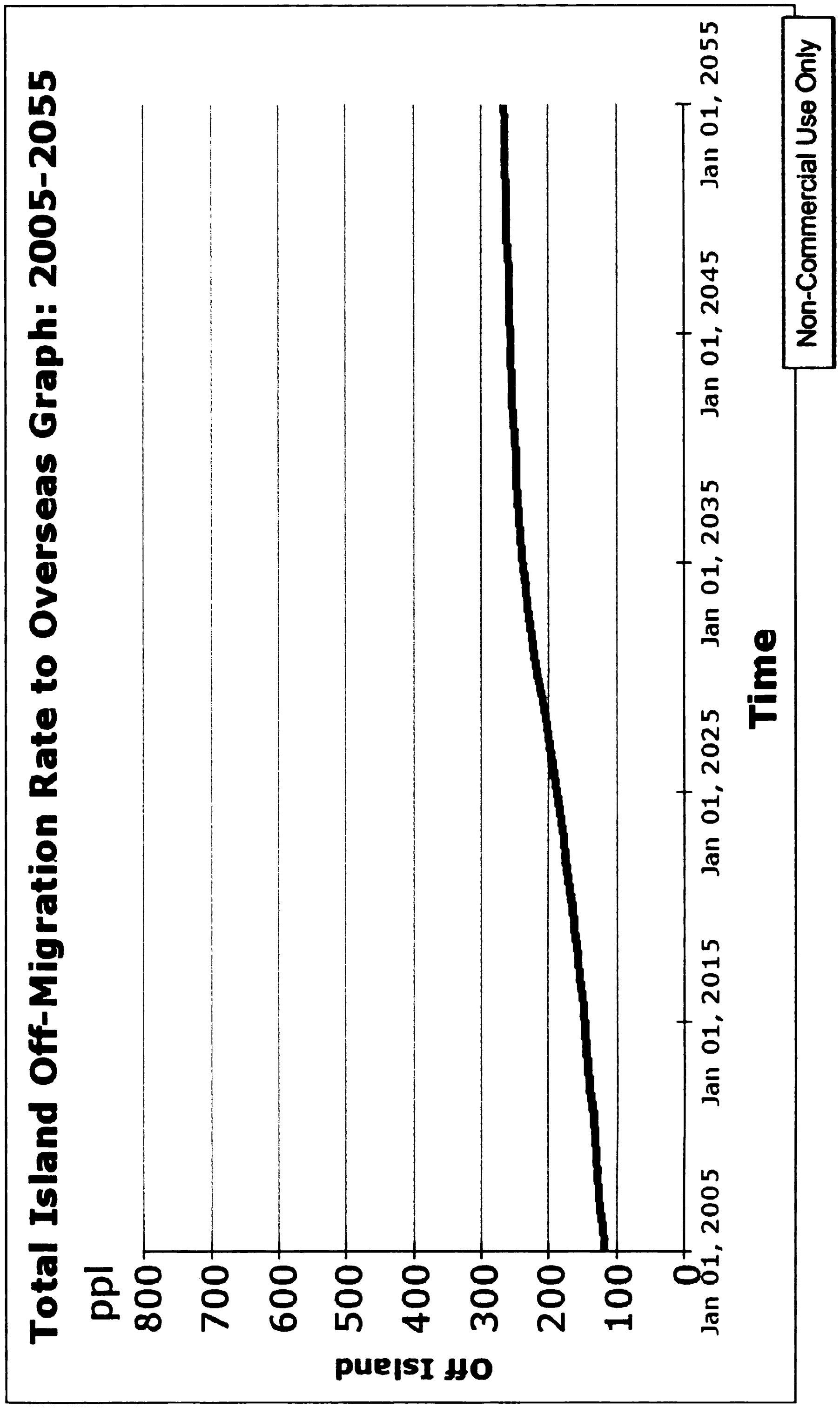


Figure 64. Model Output Graph A14

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A15

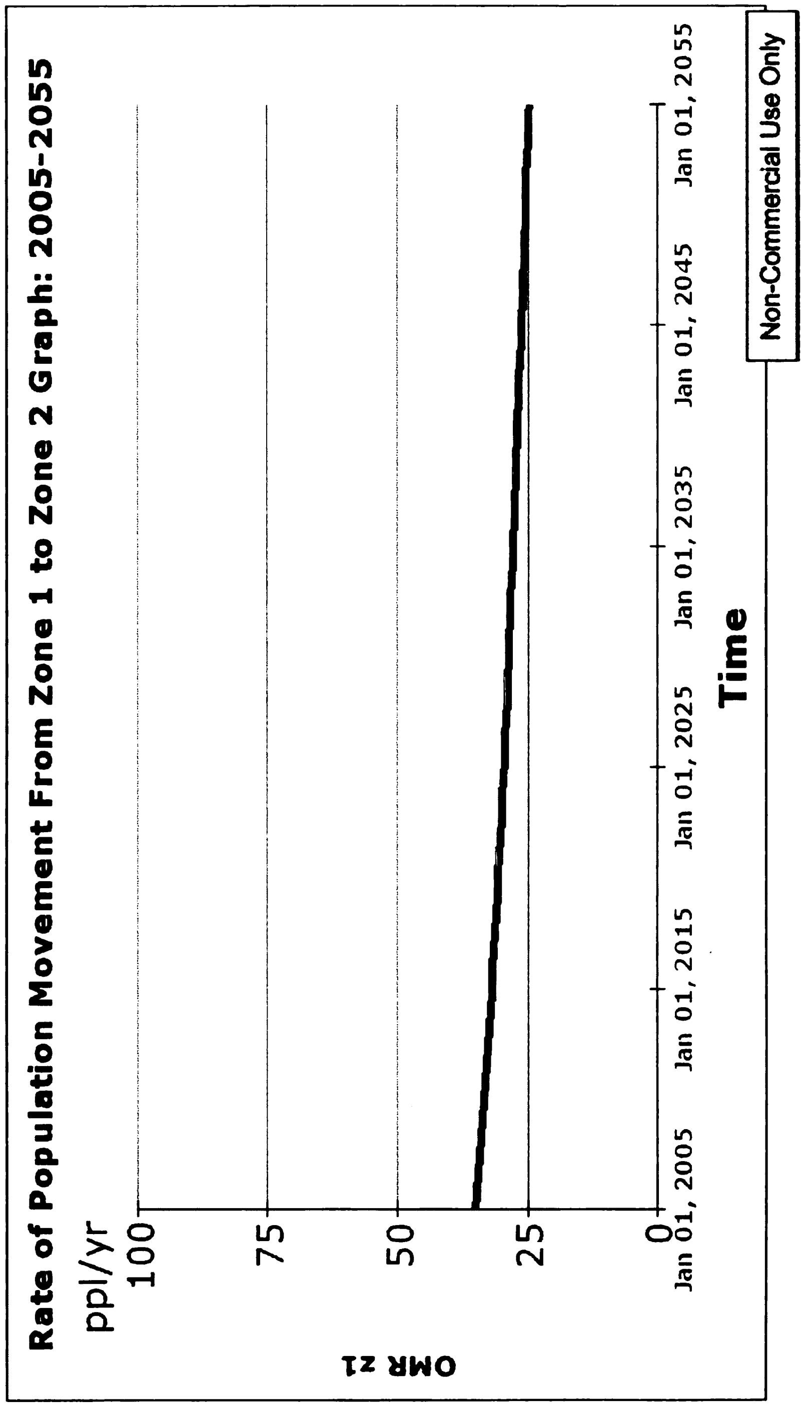


Figure 65. Model Output Graph A15

Montserrat Urban and Risk Model: Output
Scenario A: Base Scenario with Low Risk
Graph A16

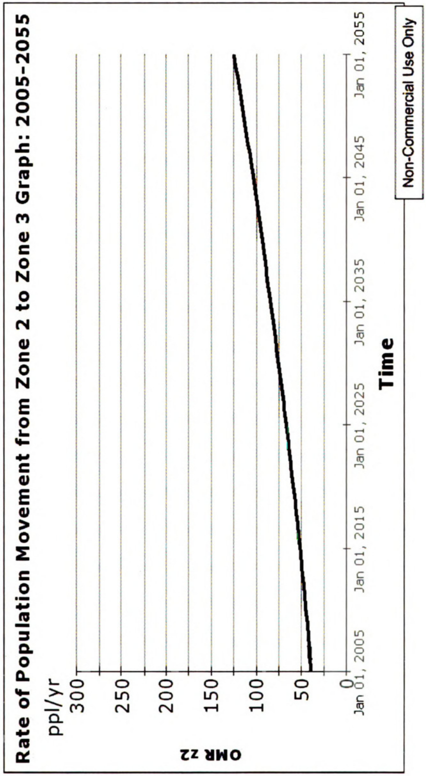


Figure 66. Model Output Graph A16

6.5.1.2 *SCENARIO A* – Interpretation of Model Output

In interpreting the initial results from running *SCENARIO A*, Figure 52 illustrates how policy choices programmed into the base scenario and in-migration rates influence population distribution between the three zones. With a low in-migration rate, and an out-migration normal set higher than the in-migration normal, population declines for zone 1 and that population flows into zone 2. As zone 1 has the highest risk, strategies to encourage a declining population in zone 1 would be desirable by emergency managers.

Figure 54 and Figure 55 depict a major developmental reconstruction boom period of from 2015 to 2030. After 15 years of rapid housing growth, the land fraction occupied for zone 2 and zone 3 quickly approaches the maximum, as depicted in Figure 61 and Figure 62. The land fraction occupied clearly limits growth.

Figure 56 depicts the decline of business structures in zone 2. These values are a direct result of the low number of initial business structures, and a slightly higher demolition rate than construction rate. Business structures in zone 2 are larger businesses such as factories or larger businesses that occupy more land per business structure, but also provide also more employment per business structure. Implicit in these results are the policy decisions that zone 2 is used exclusively for these larger business structures. Given that zone 2 faces a higher risk than zone 3, the base model reflects a strategy where deliberate choices were made to place such business structures in this zone. The reasoning behind such action is that since they are only in use a portion of the day such structures in zone 2 would limit risk exposure to workers (whereas increased housing in place of these business structures would be occupied 24 hours a day), also it would be easier to evacuate a few larger facilities than a large number of smaller facilities (such as in zone 3), and in the event they were lost, while damaging to the economy the smaller businesses providing local services would be still be operate from zone 3. Zone 2 businesses structures would primarily service off-shore clients, while zone 1 business structures would service local clients. However, as the number of these businesses declines, there will be substantial job loss, as depicted in Figure 58.

While there is population movement between the zones and off the island, the values for population movement are not substantial, and the rate is gradual as depicted in Figure 64, Figure 65, and Figure 66.

6.5.2 *SCENARIO B* – Medium Risk

SCENARIO B is named medium risk.

In *SCENARIO B*, all factors in the urban model are kept constant however over the 50 year period risk gradually increases to four times the initial risk level as depicted in Figure 75 and Figure 76. As the base urban model operates, the impacts of increasing risk are reflected in several aspects of this scenario. In *SCENARIO B*, the scenario's population end value is approximately 2,000 persons less than the established goal of 10,000 persons as illustrated in Figure 67.

This scenario is more likely to fit the reality on Montserrat than *SCENARIO A*. Given the current risk assessment of the volcano, it is likely that the volcano on Montserrat will present risks to its citizens for many years to come. The model is based on the assumption that the while the risk will gradually increase during the next five decades. As discussed more fully in Chapter 7, *SCENARIO B* was set a limit where risk has a noticeable impact on the population, housing, jobs, etc. At risk levels in between those in *SCENARIO A* and *SCENARIO B*, the output of the model will be similar to the base model, with the exception of a smaller rate of population increase as the risk increases.

6.5.2.1 *SCENARIO B* – Model Output

The following Figures 67-82 depict the results from *SCENARIO B*.

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B1

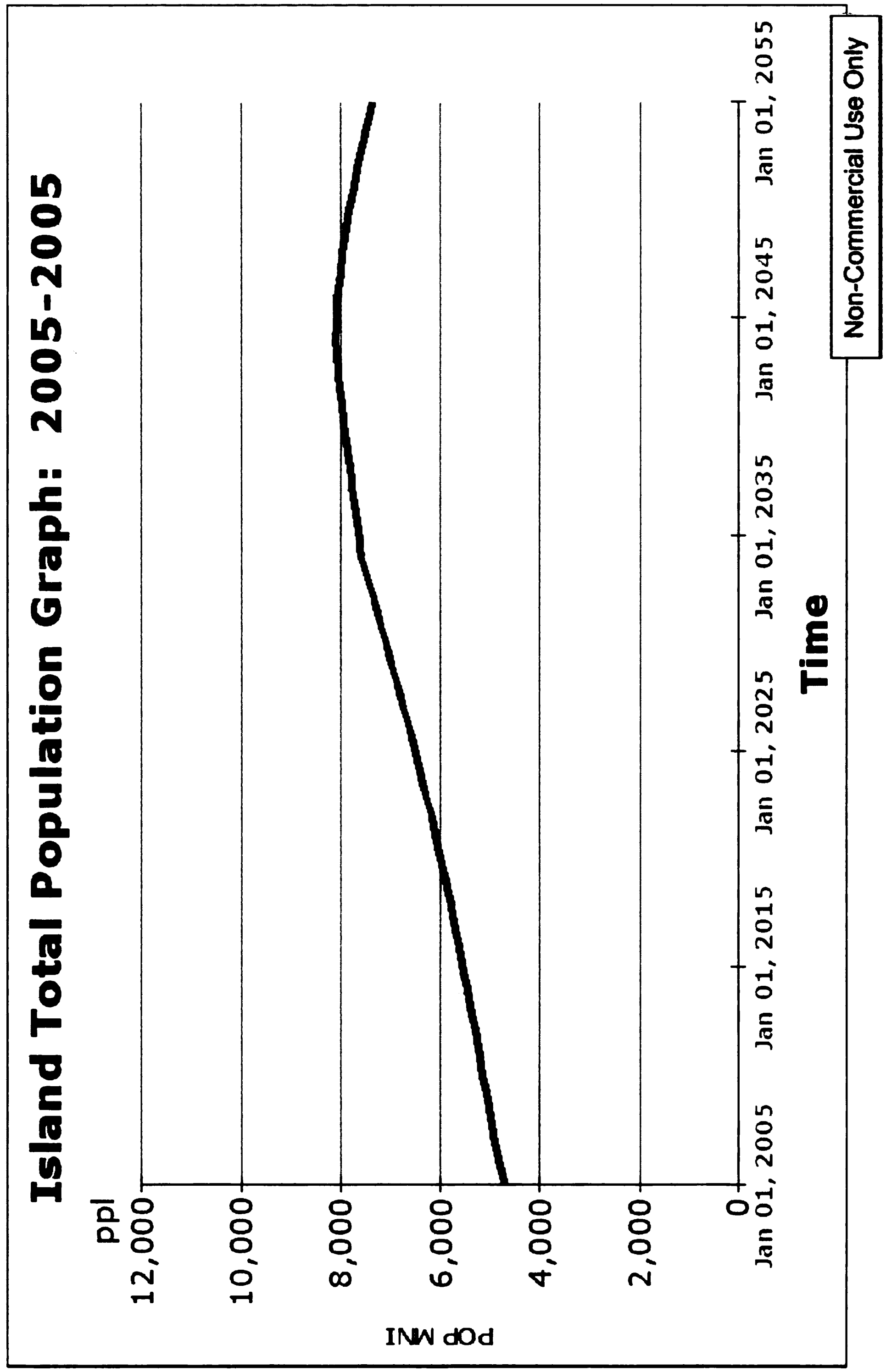


Figure 67. Model Output Graph B1

Montserrat Urban and Risk Model: Output
<u>Scenario B: Medium Risk</u>
Graph B2

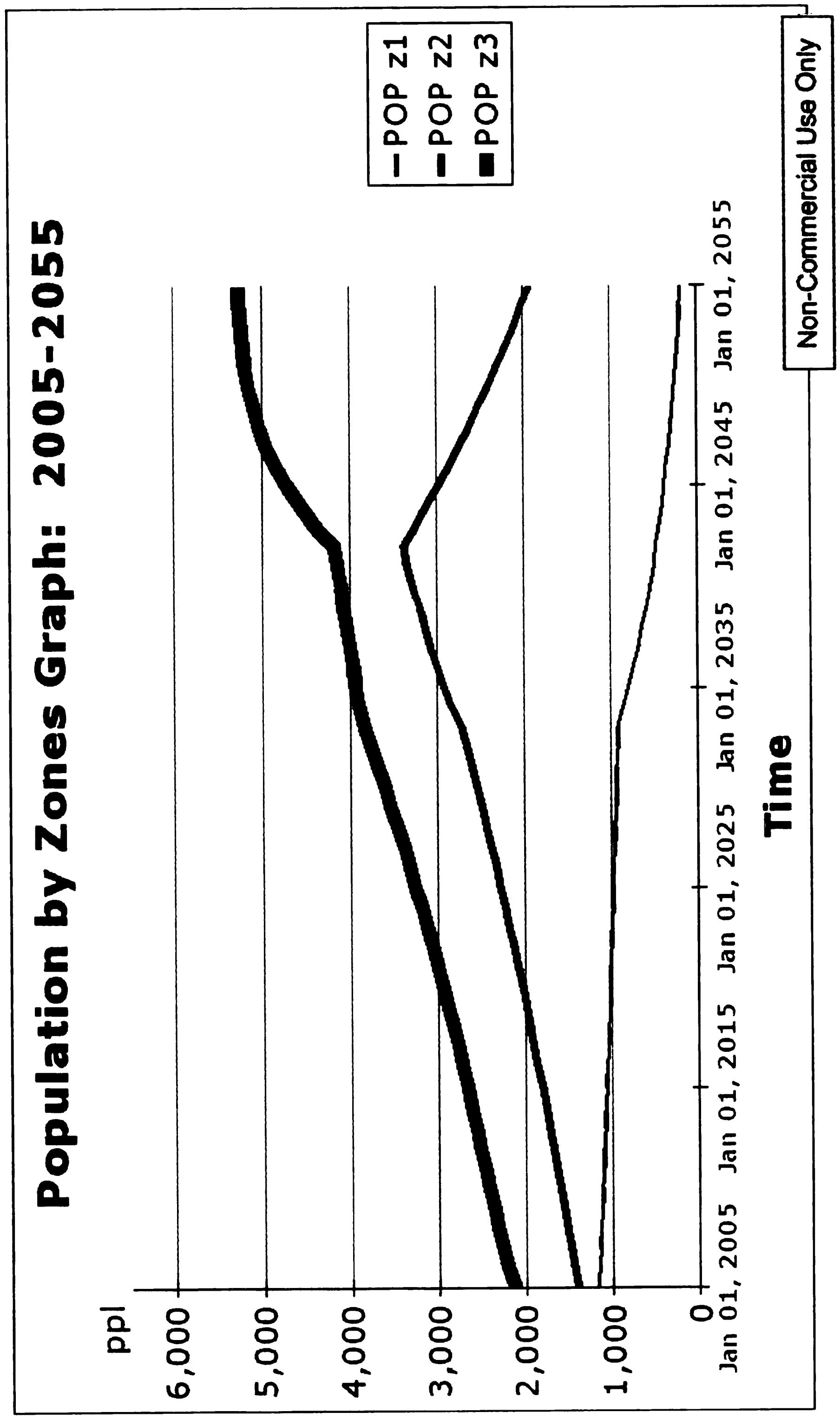


Figure 68. Model Output Graph B2

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B3

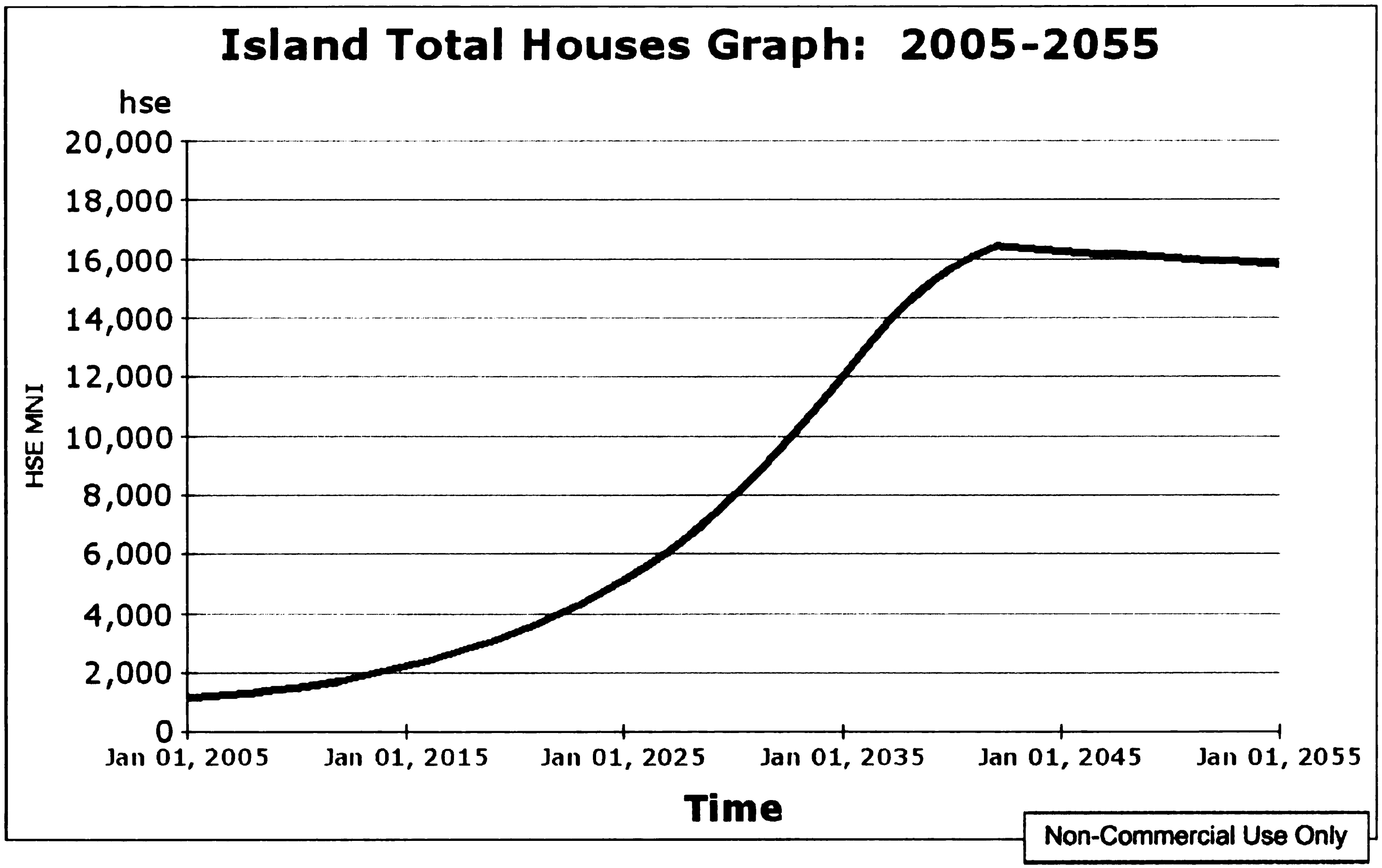


Figure 69. Model Output Graph B3

Montserrat Urban and Risk Model: Output
<u>Scenario B: Medium Risk</u>
Graph B4

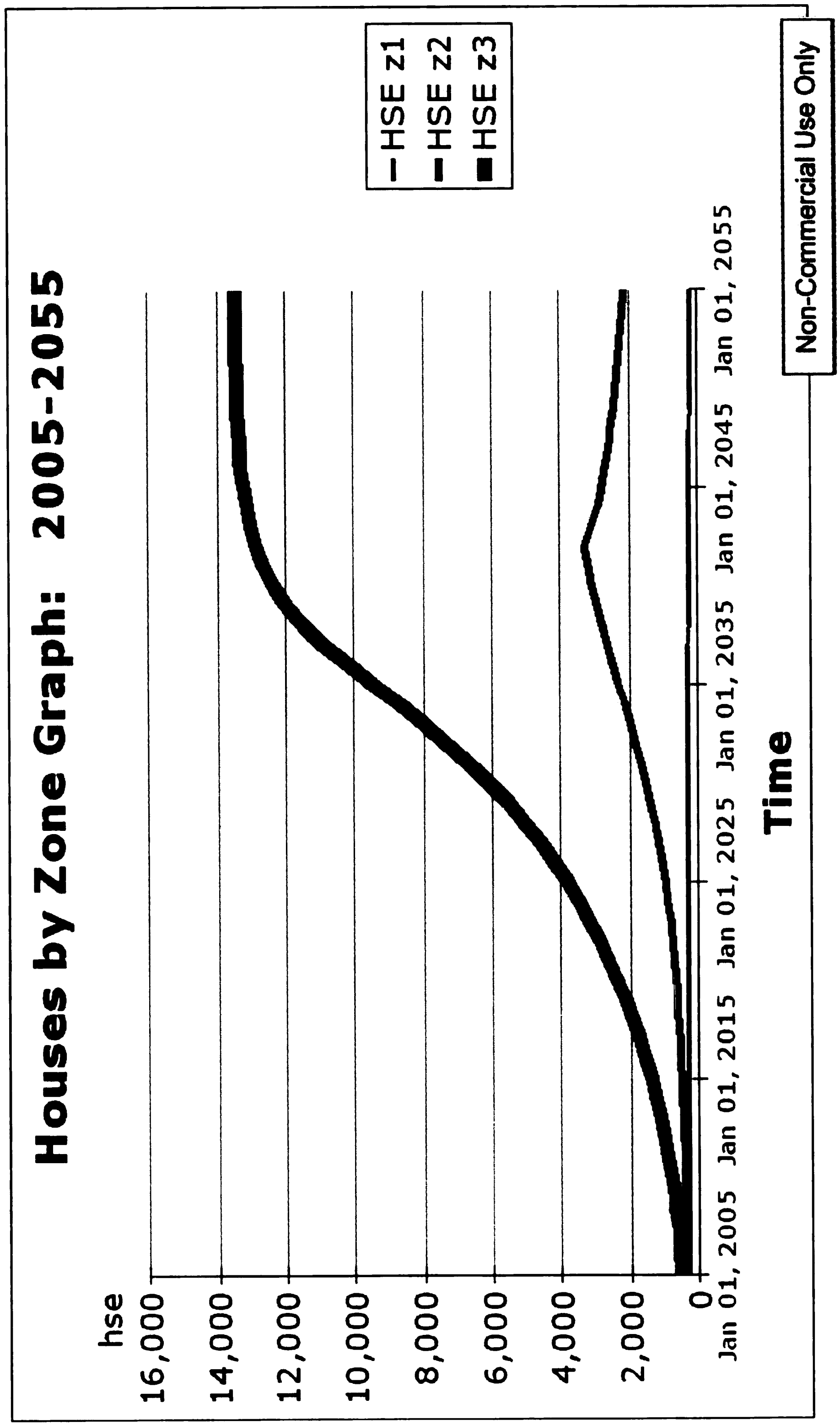


Figure 70. Model Output Graph B4

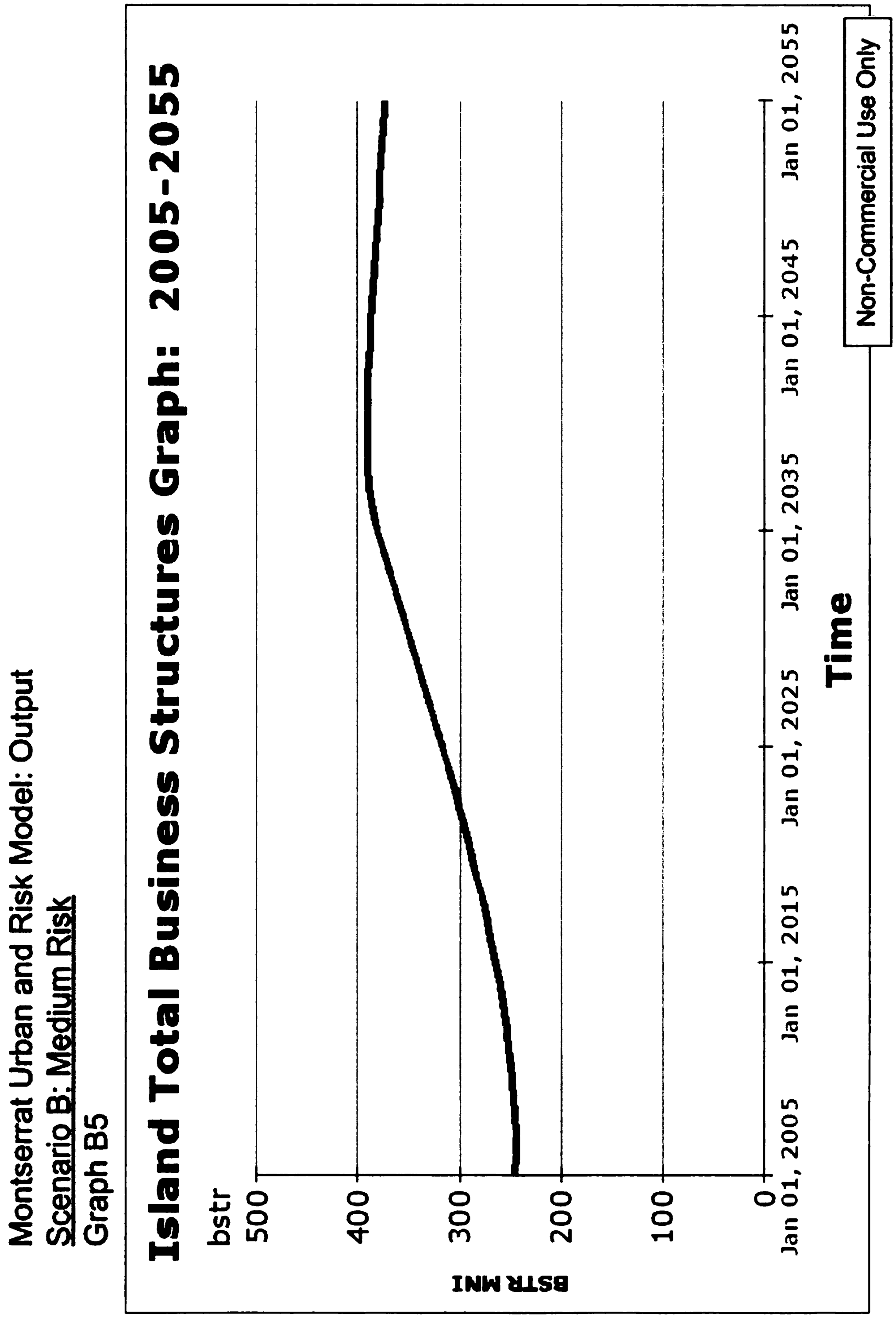


Figure 71. Model Output Graph B5

Montserrat Urban and Risk Model: Output
<u>Scenario B: Medium Risk</u>
Graph B6

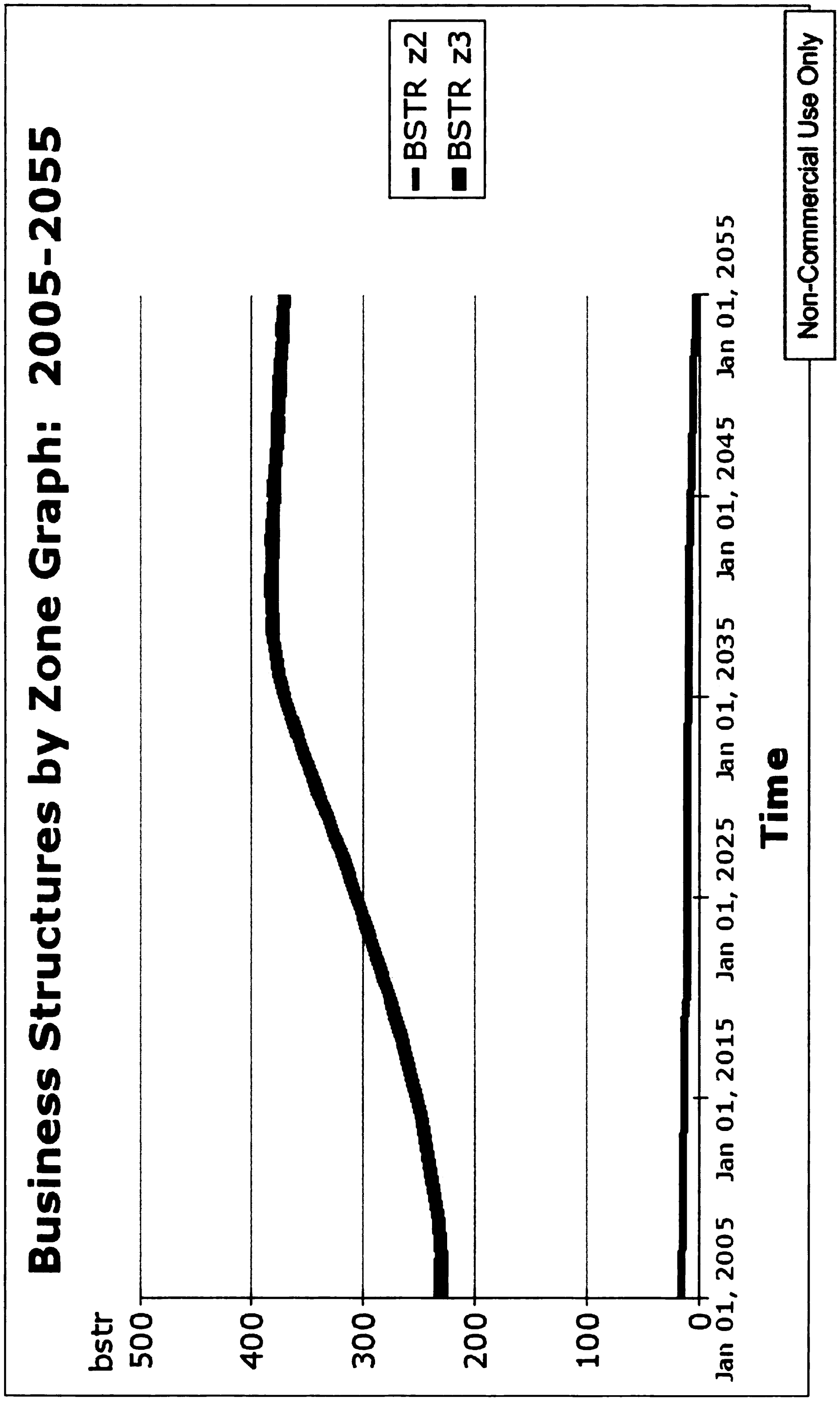


Figure 72. Model Output Graph B6

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B7

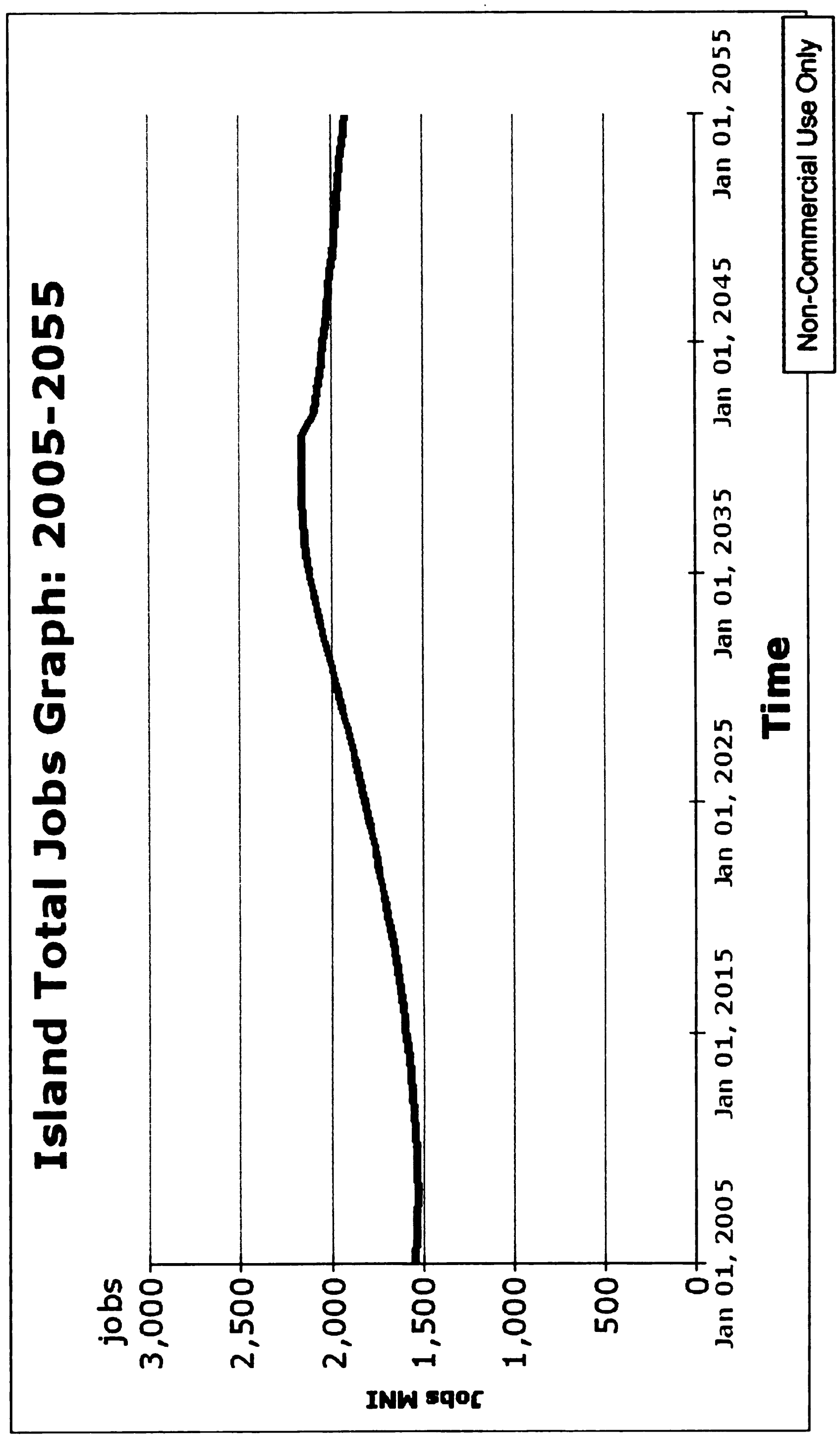


Figure 73. Model Output Graph B7

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B8

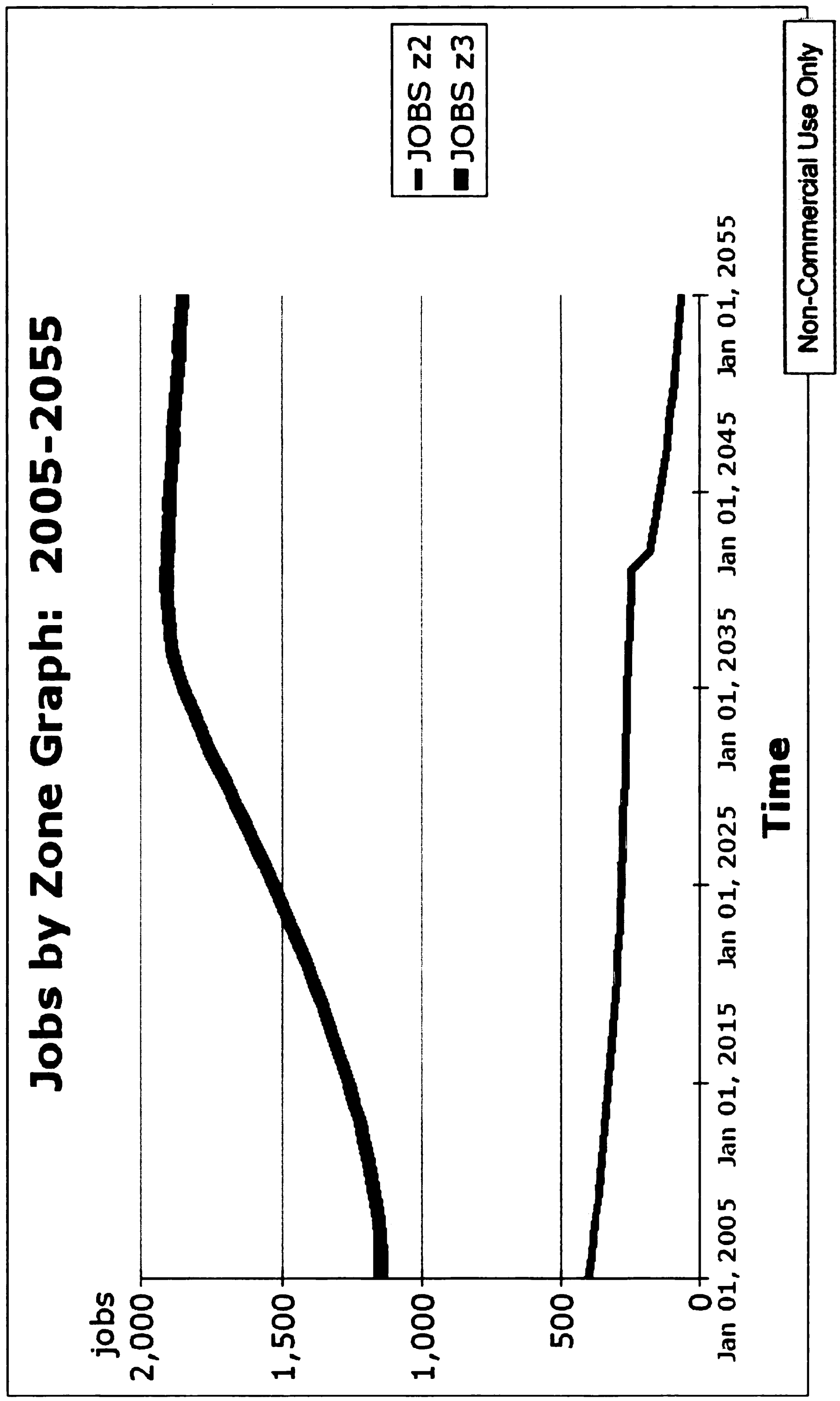


Figure 74. Model Output Graph B8

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B9

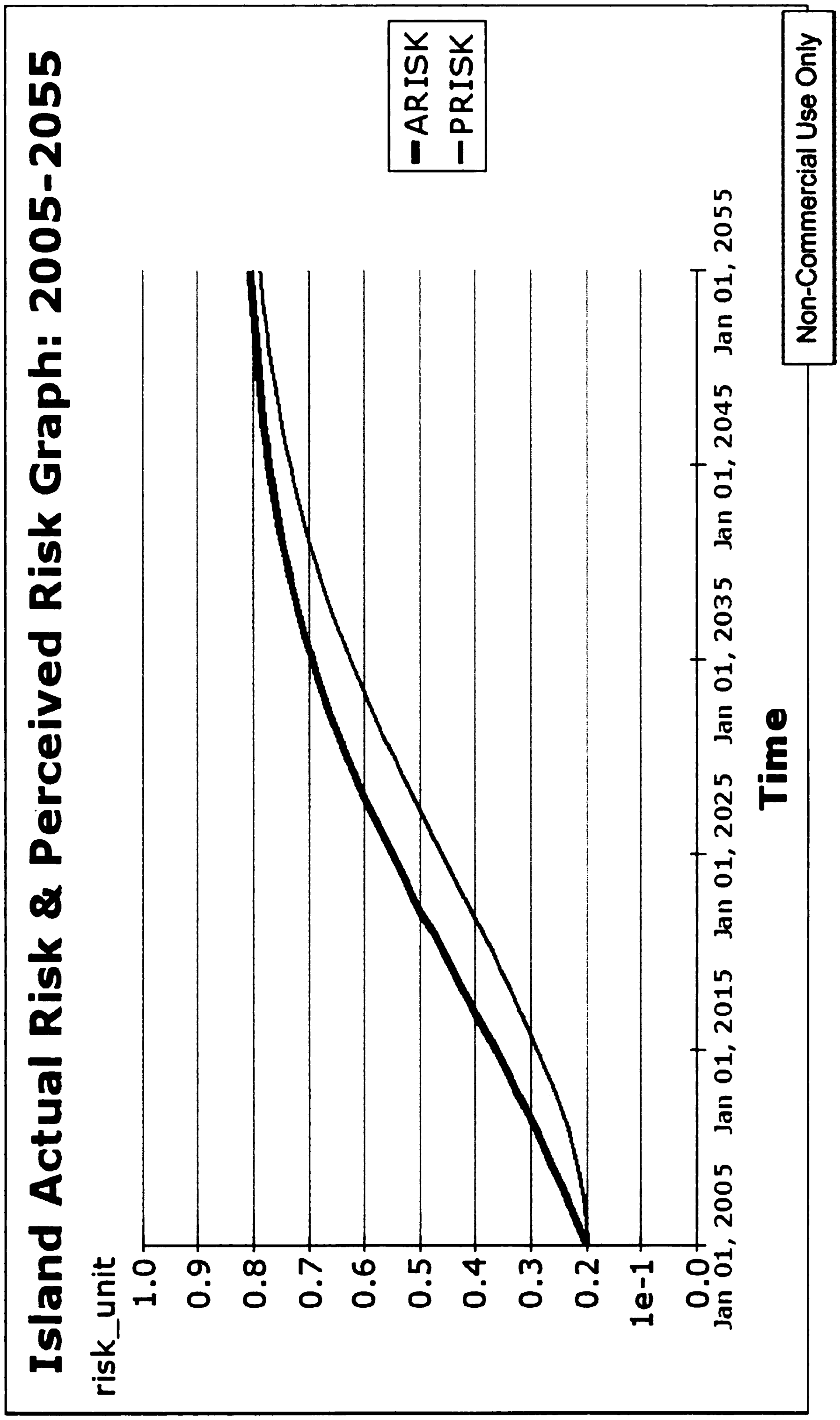


Figure 75. Model Output Graph B9

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B10

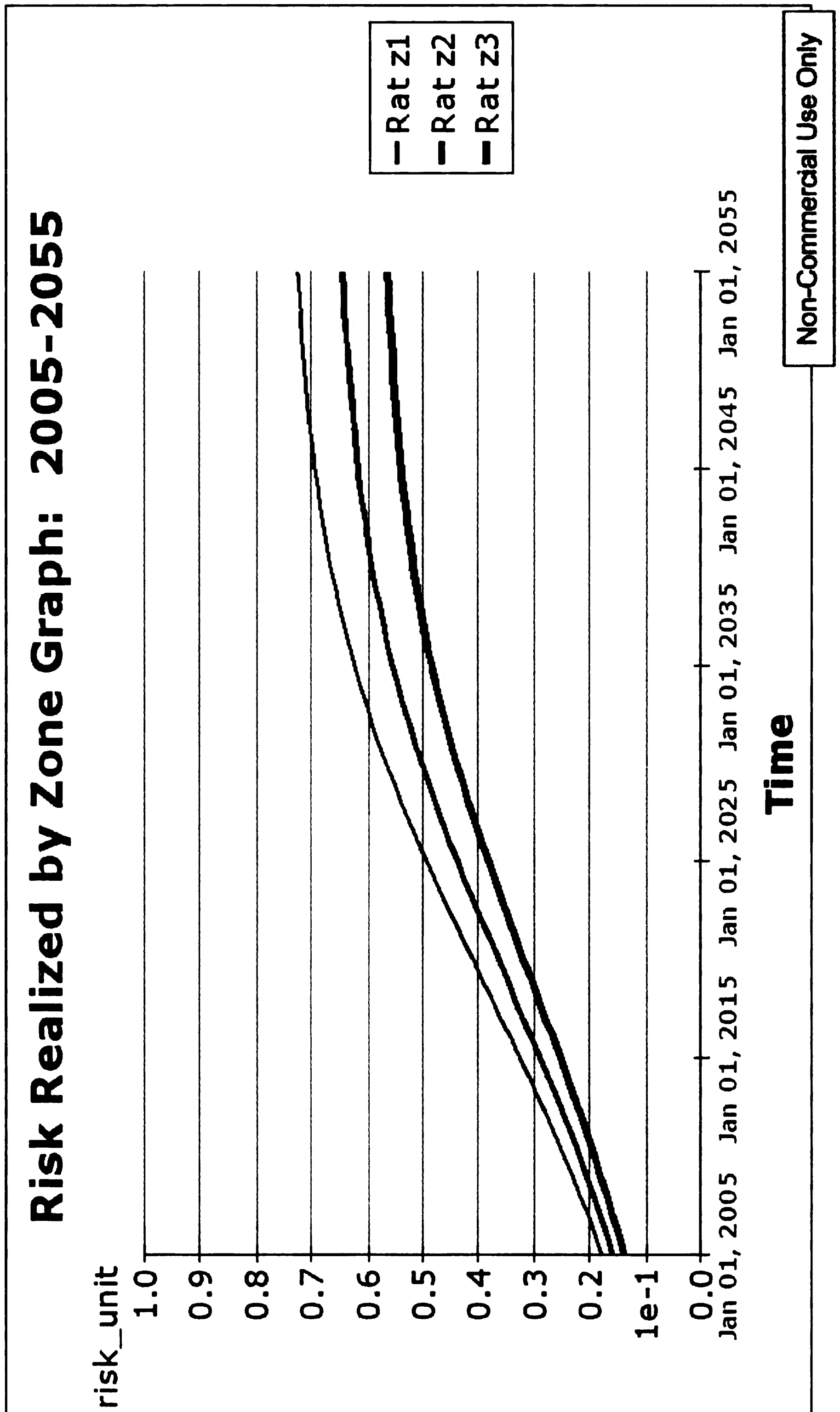


Figure 76. Model Output Graph B10

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B11

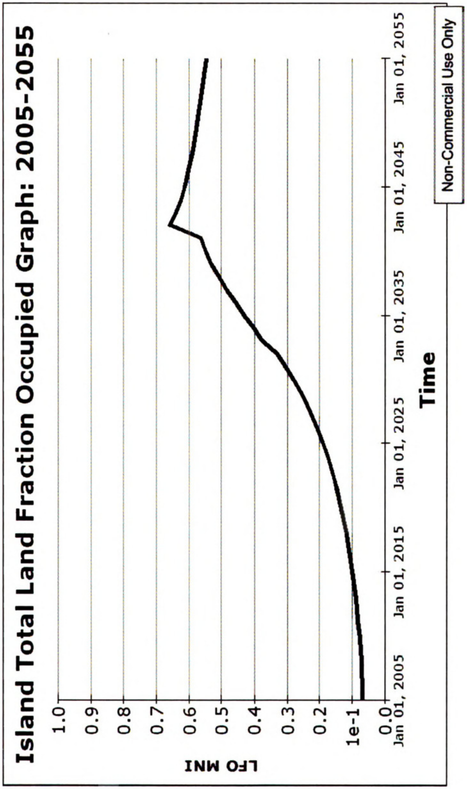


Figure 77. Model Output Graph B11

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B12

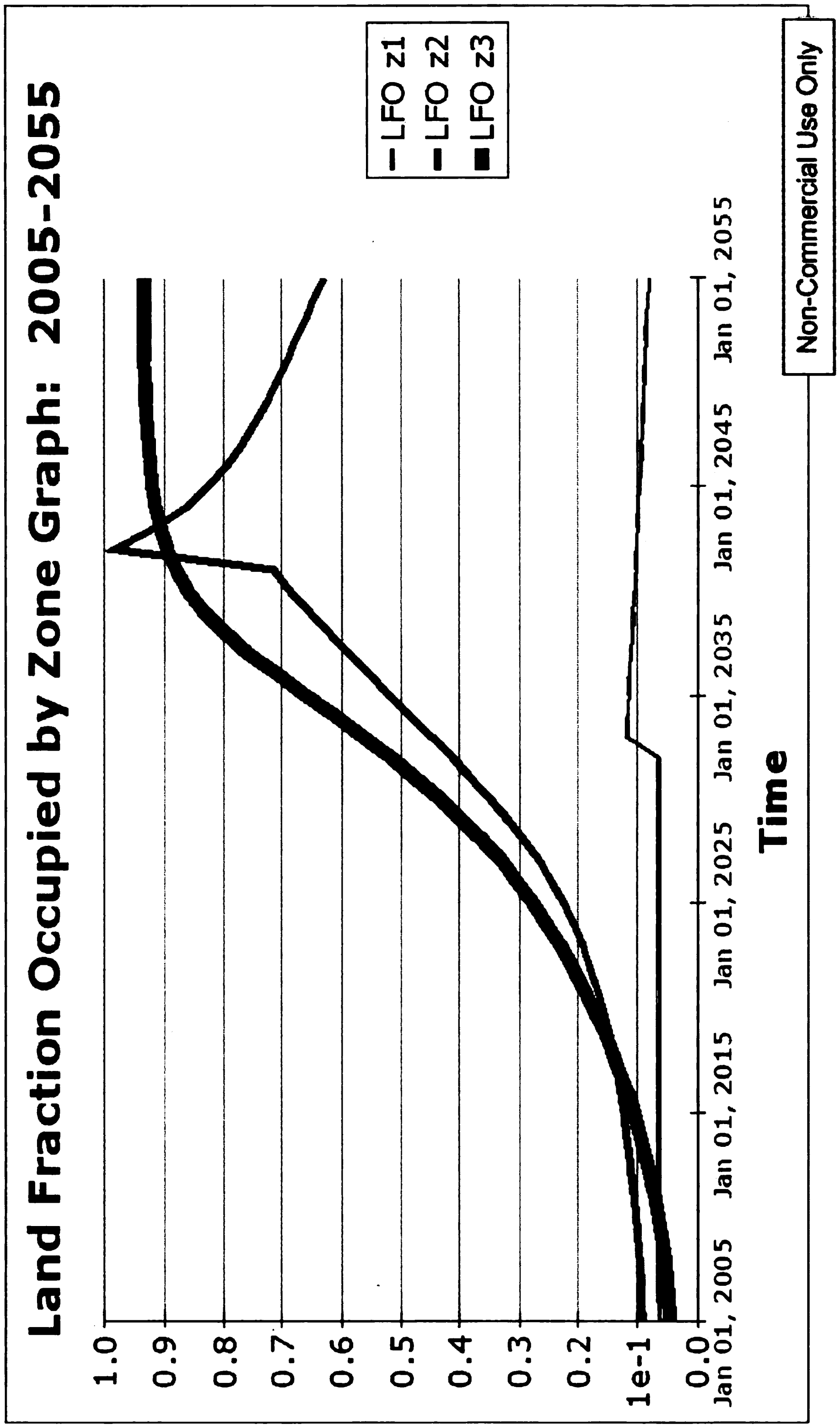


Figure 78. Model Output Graph B12

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B13

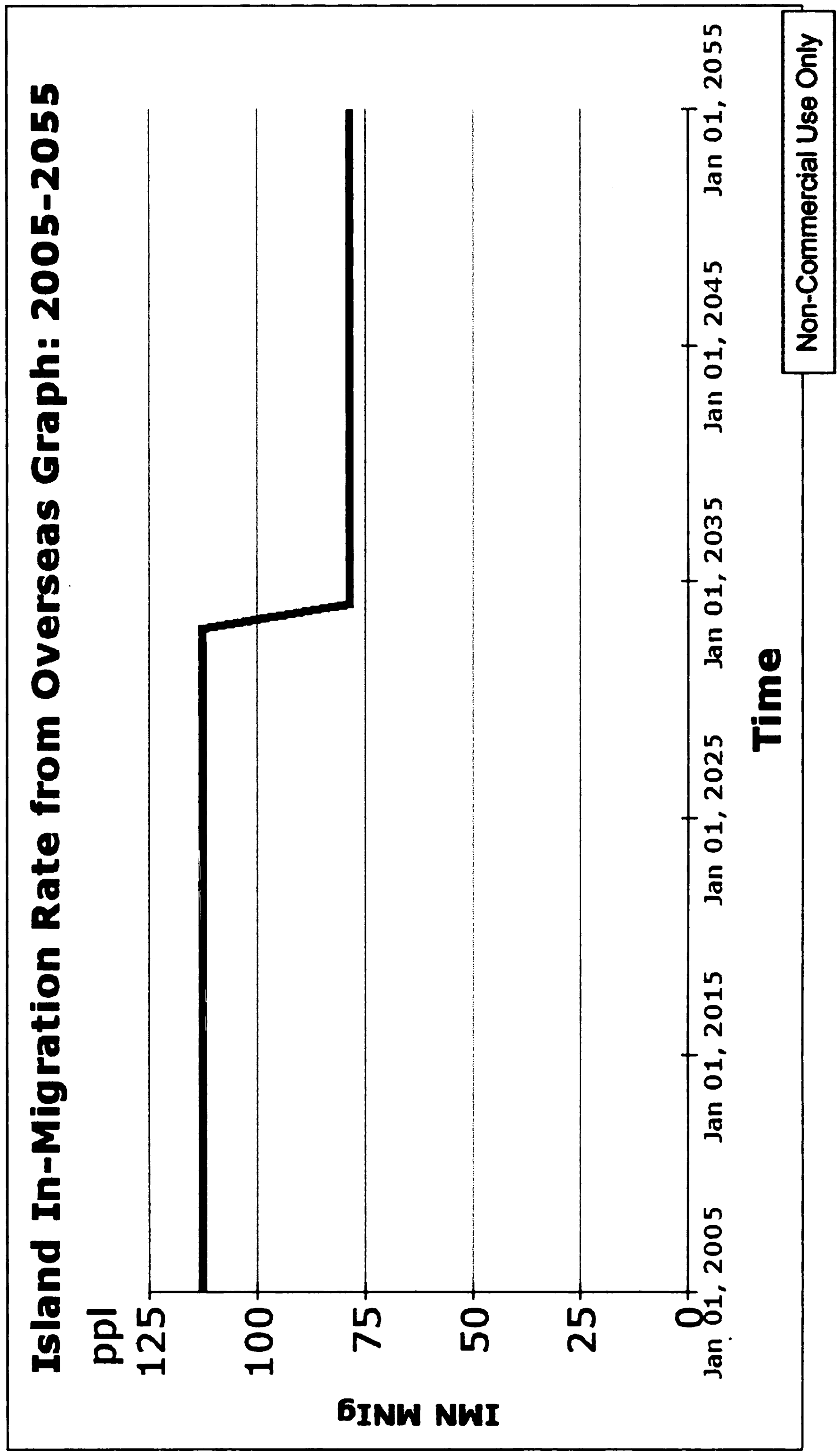


Figure 79. Model Output Graph B13

Montserrat Urban and Risk Model: Output

<u>Scenario B: Medium Risk</u>

Graph B14

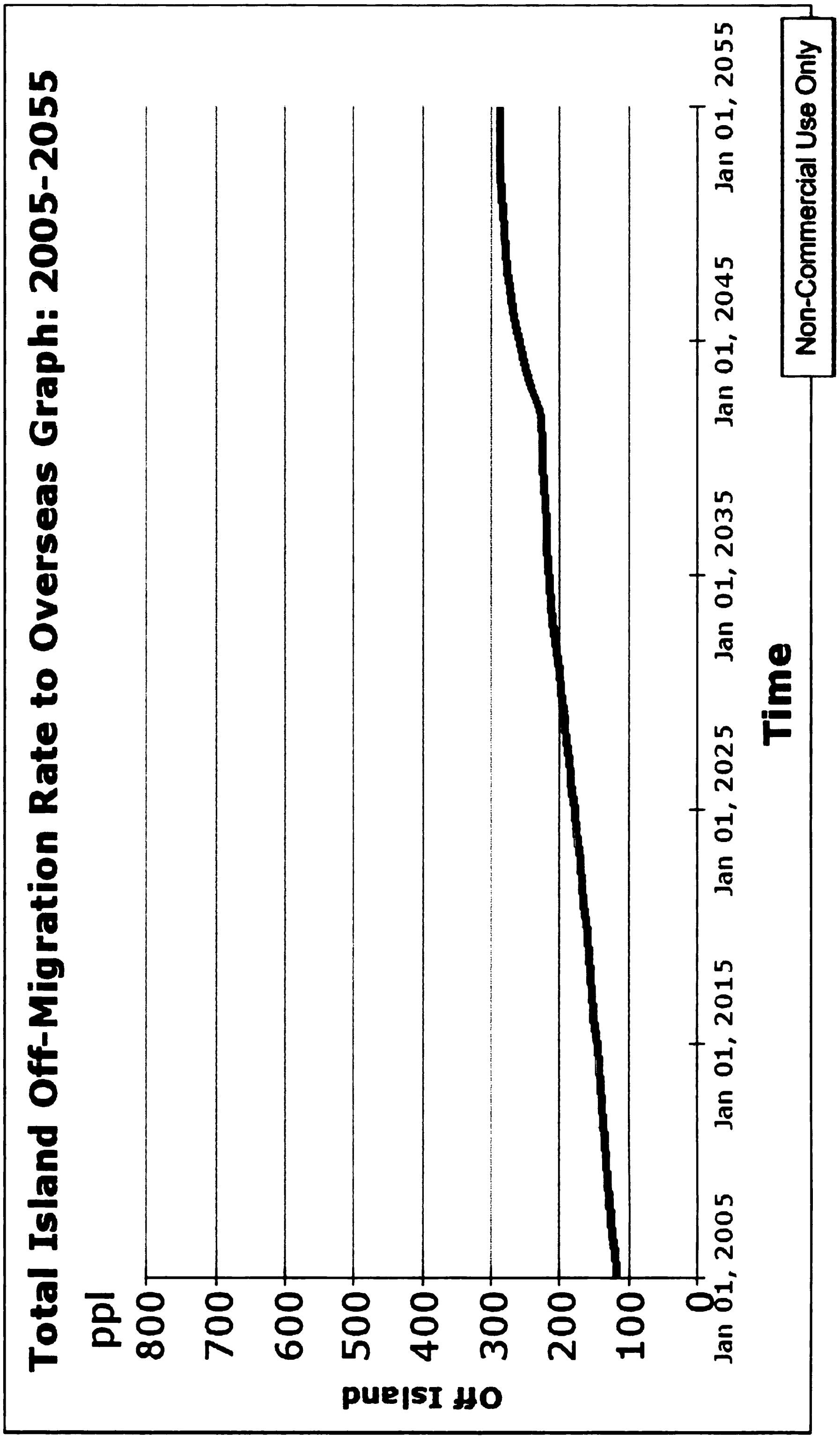


Figure 80. Model Output Graph B14

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B15

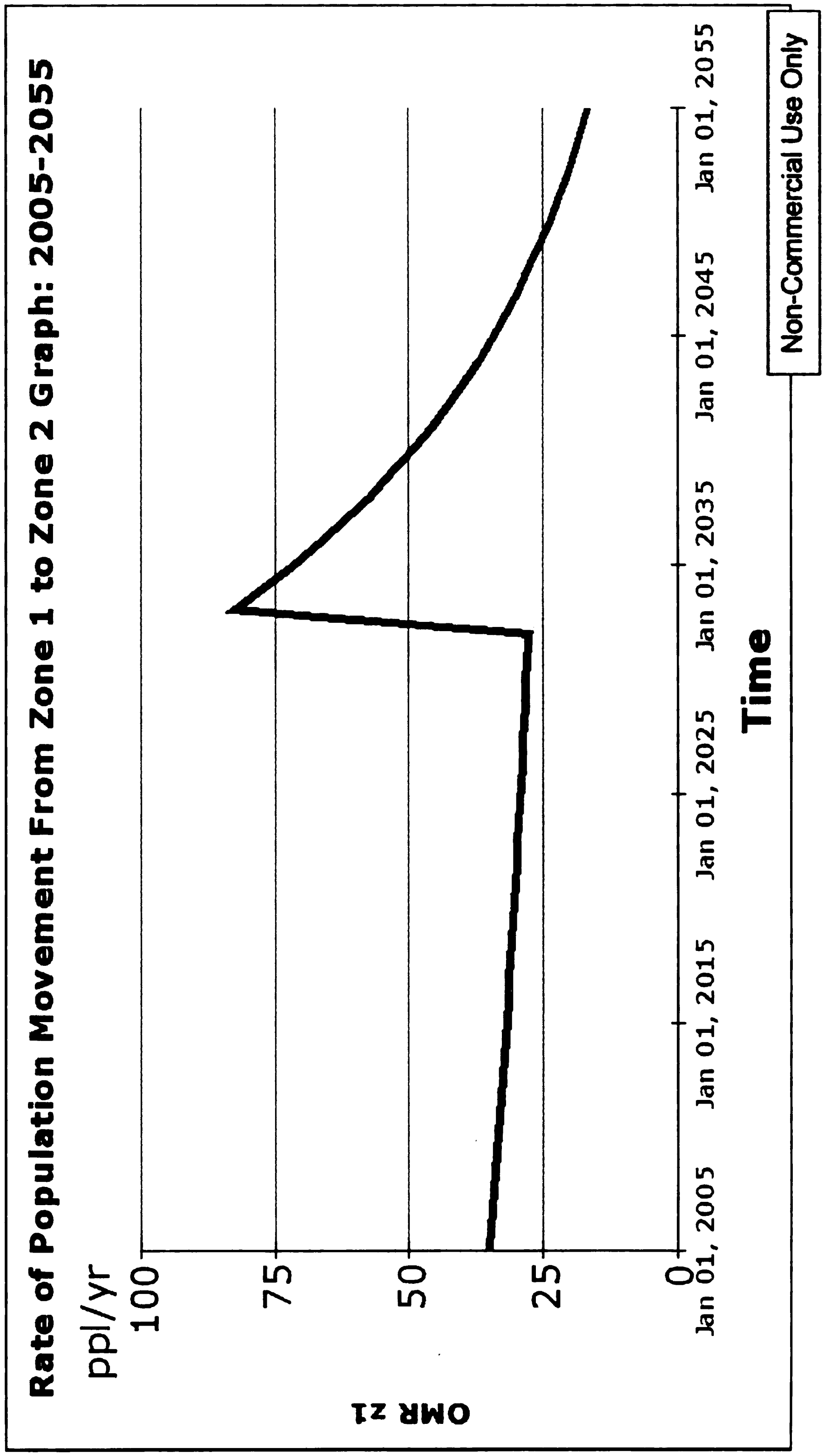


Figure 81. Model Output Graph B15

Montserrat Urban and Risk Model: Output
Scenario B: Medium Risk
Graph B16

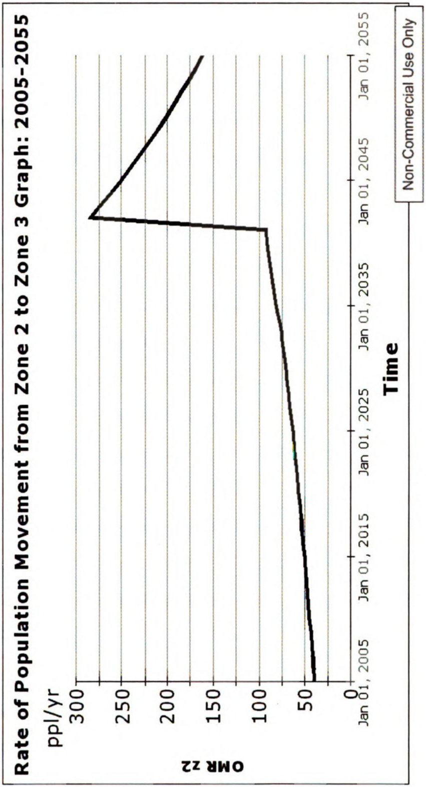


Figure 82. Model Output Graph B16

6.5.2.2 *SCENARIO B* – Interpretation of Model Output

The effects of risk are evident in Figure 68, since in this scenario zone 1 and zone 2 risk increases past a threshold limit (set to 0.6) where the construction rate is reduced, some structures are lost, and volcanic activity reduces the amount of land available for development. The population reacts to these changes by leaving zone 2 and moving into zone 3 between 2040 and 2045.

Figure 75 illustrates how risk perception reacts to actual risk with a delay in perceiving the actual risk. Figure 79 illustrates a drop in the in-migration to the island related to when some people who would have went to the island perceive the island to be too dangerous and cancel their travel.

Figure 78 depicts volcanic activity rendering portions of zone two useless between 2040 and 2045. The land fraction occupied spikes to near 1.0 the then declines as housing and business structures are destroyed. Despite this freeing up of land available for development, the high risk level will likely keep people from exploiting the opportunities created for development by a lowered land fraction occupied. Related effects can also be noticed in Figure 70 with a decline of the number of houses in zone 2 and a drastic population movement from zone 1 to zone 2 (see Figure 81) and from zone 2 to zone 3 (see Figure 82).

6.5.3 *SCENARIO C* – Medium Risk with Step

SCENARIO C is named medium risk with step.

In *SCENARIO C*, risk again increases by four times over the 50 year period, however as opposed to the gradual increase in risk level as depicted in *SCENARIO B*, after 10 years of gradual increase, the risk levels jump and increase quicker. This scenario represents how the unpredictable nature of the volcano can be incorporated into the model. Variations in risk of a represented by a step increase cause a risk threshold (0.6) to be reached in zone 1 one and zone 2 with impacts on population, housing, business, jobs, and land fraction occupied.

In the systems dynamics modeling method, a step function is used to achieve the effect of a jump in actual risk levels. In a similar fashion, the actual risk over time can be altered to try to simulate different hazard conditions. As continued scientific assessments take place and more is learned about the behavior of Montserrat's volcano, it may be possible to determine potential types of volcanic behavior, and to integrate that behavior into risk functions of the model.

6.5.3.1 *SCENARIO C* – Model Output

The following Figures 83-98 depict the results of *SCENARIO C*.

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C1

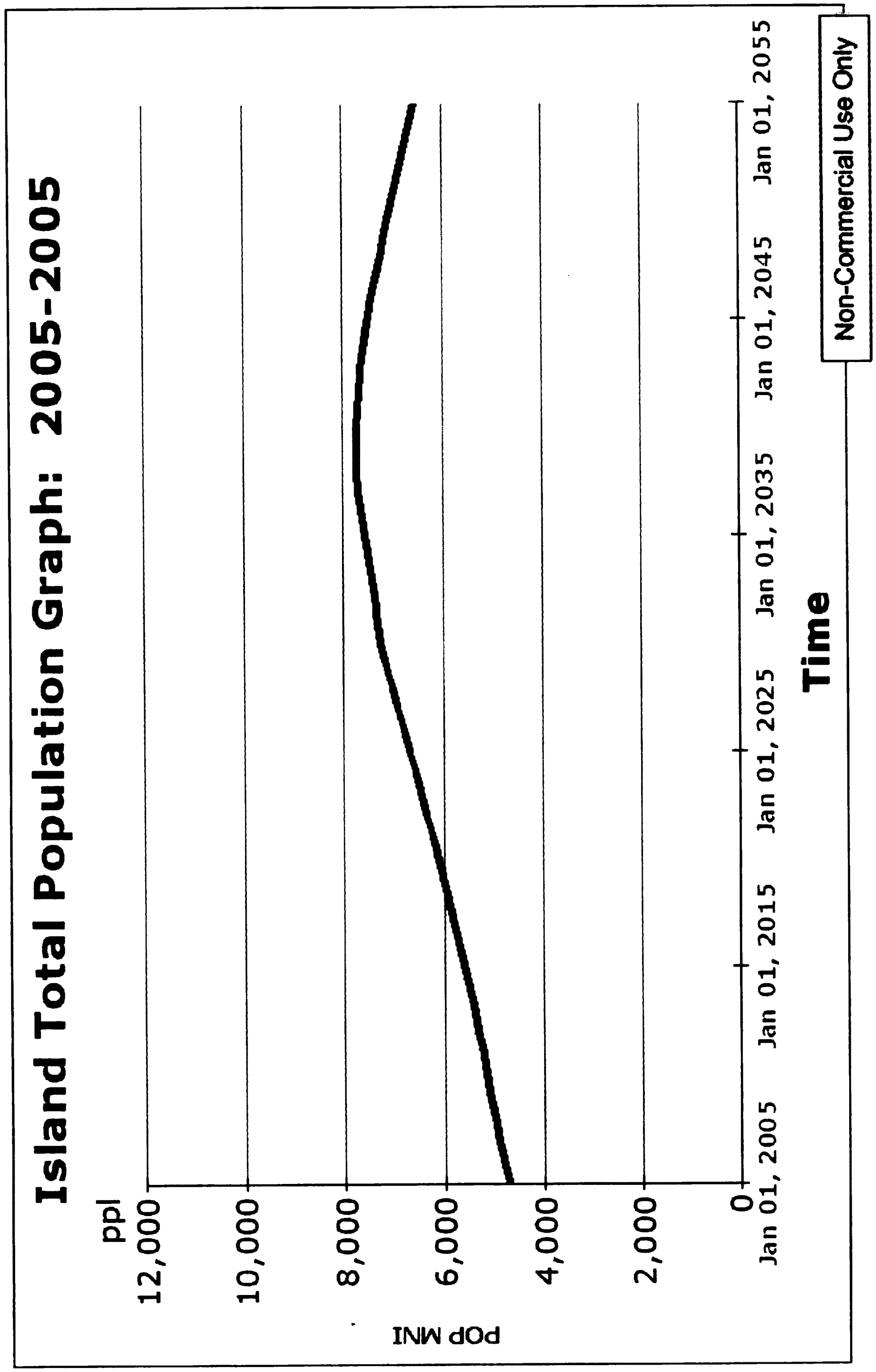


Figure 83. Model Output Graph C1

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C2

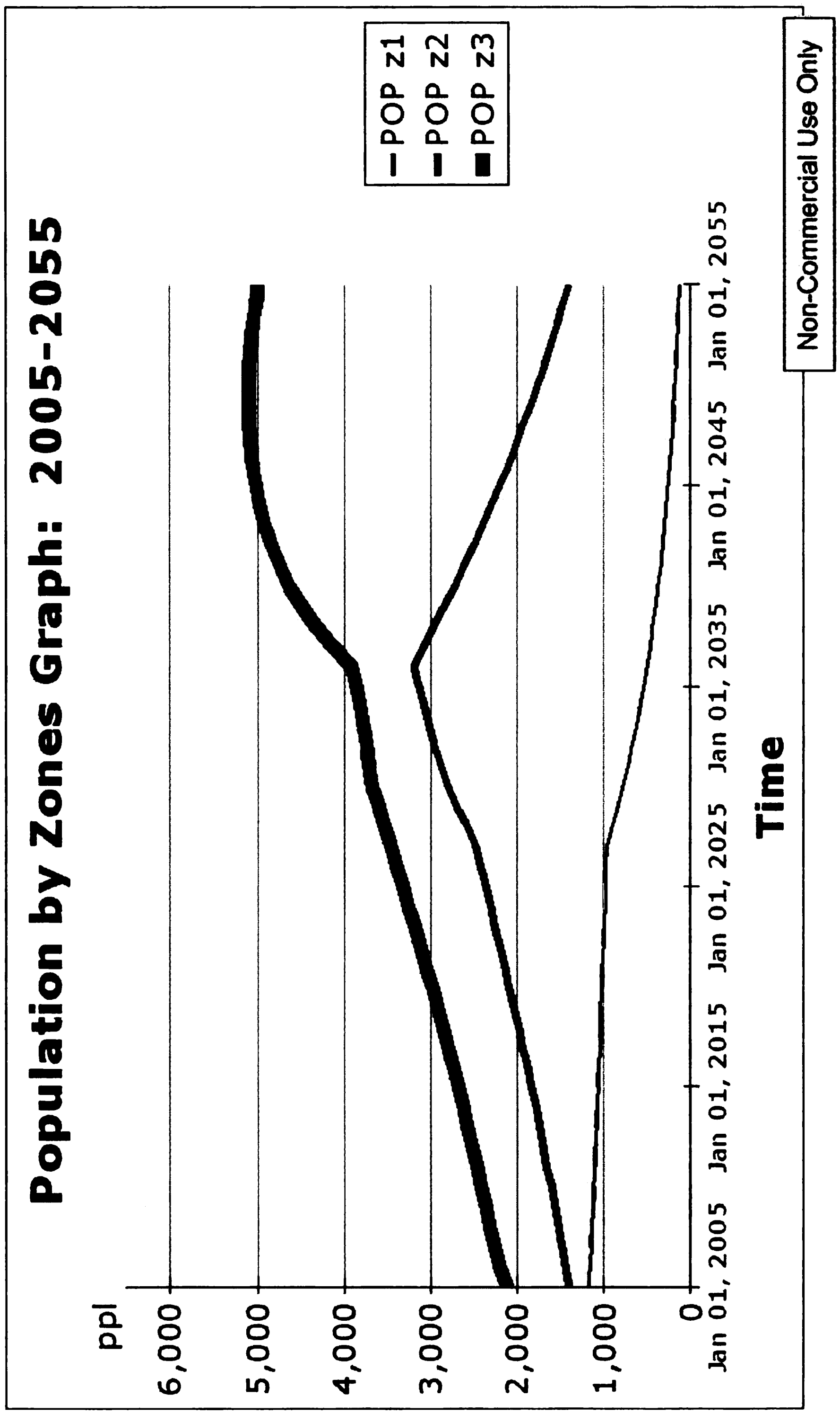


Figure 84. Model Output Graph C2

Risk Model: Output

Montserrat Urban and Risk Model: Output

Scenario C: Medium Risk with Step

Graph C3

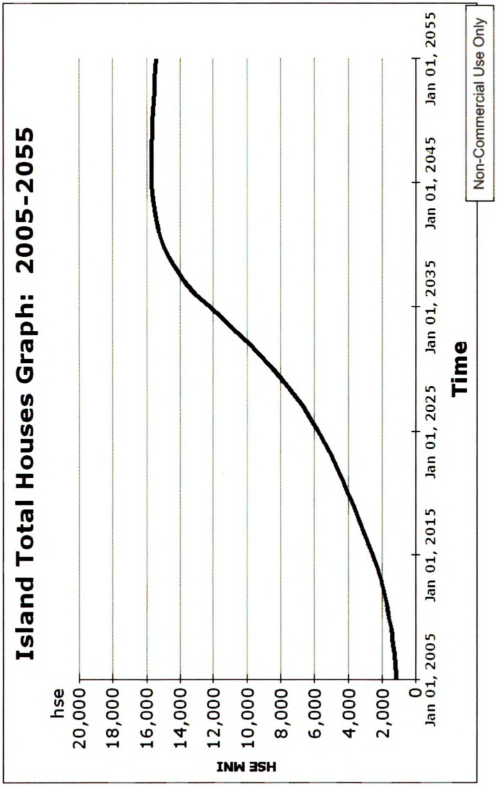


Figure 85. Model Output Graph C3

Montserrat Urban and Risk Model: Output
<u>Scenario C: Medium Risk with Step</u>
Graph C4

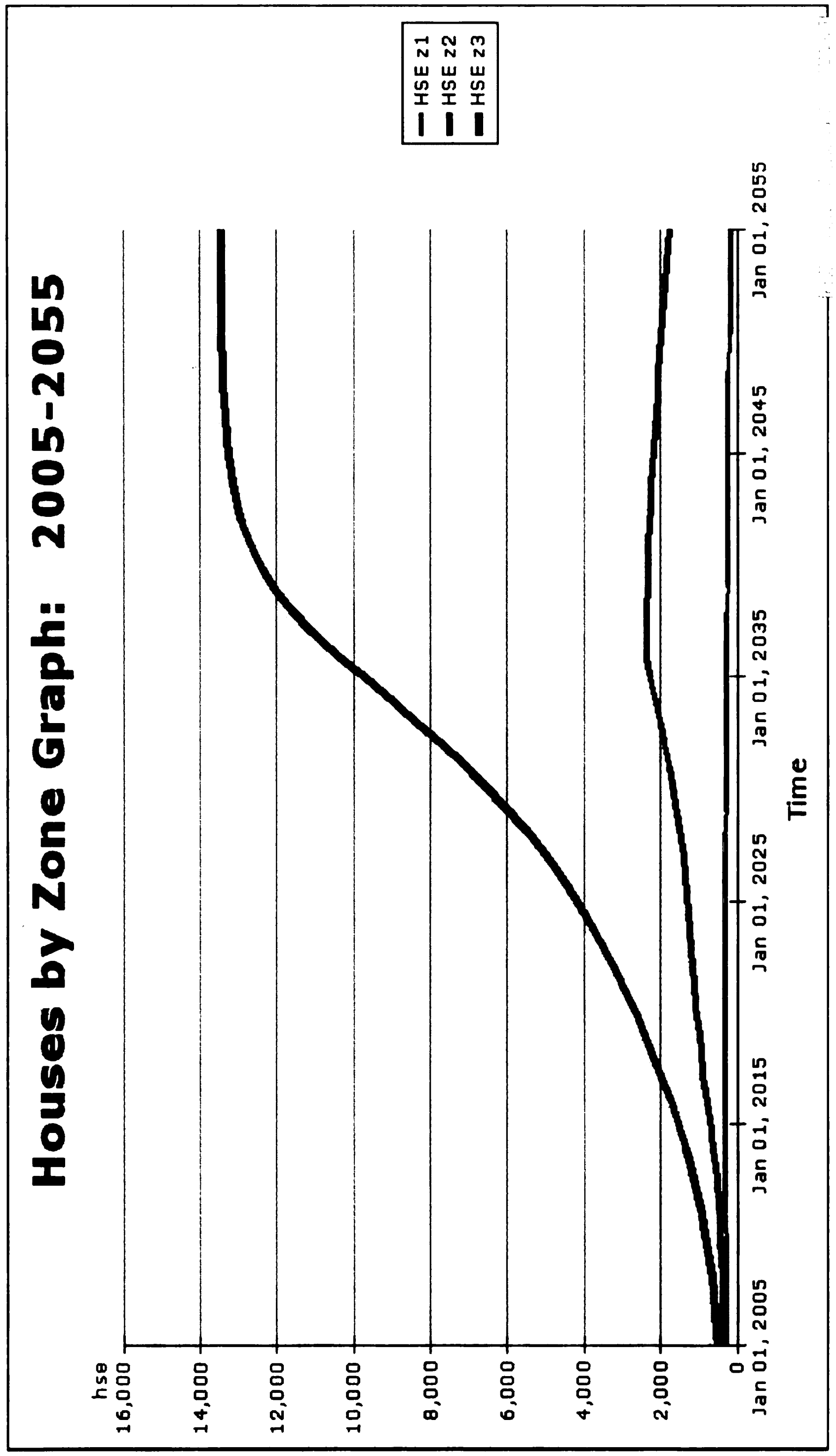


Figure 86. Model Output Graph C4

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C5

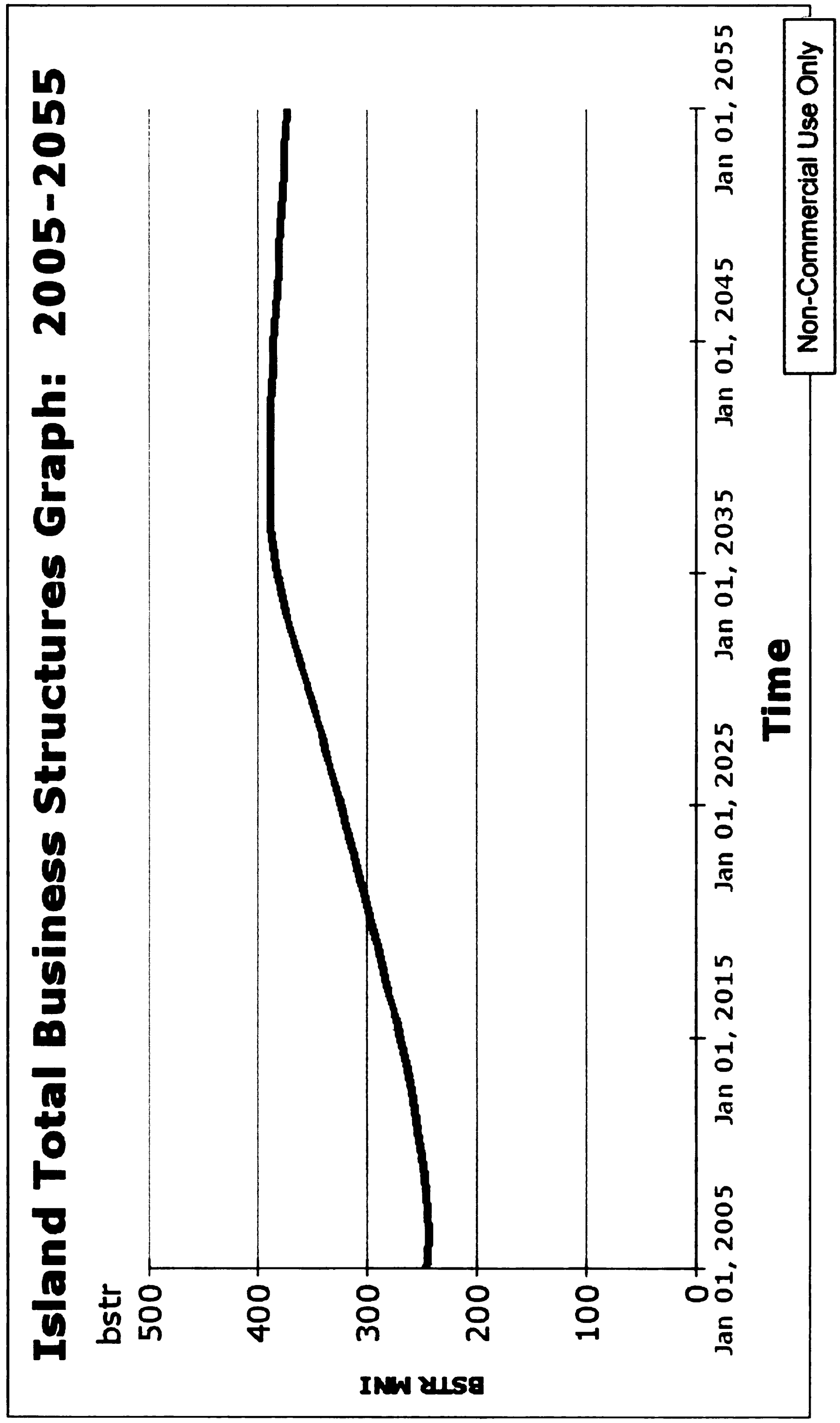


Figure 87. Model Output Graph C5

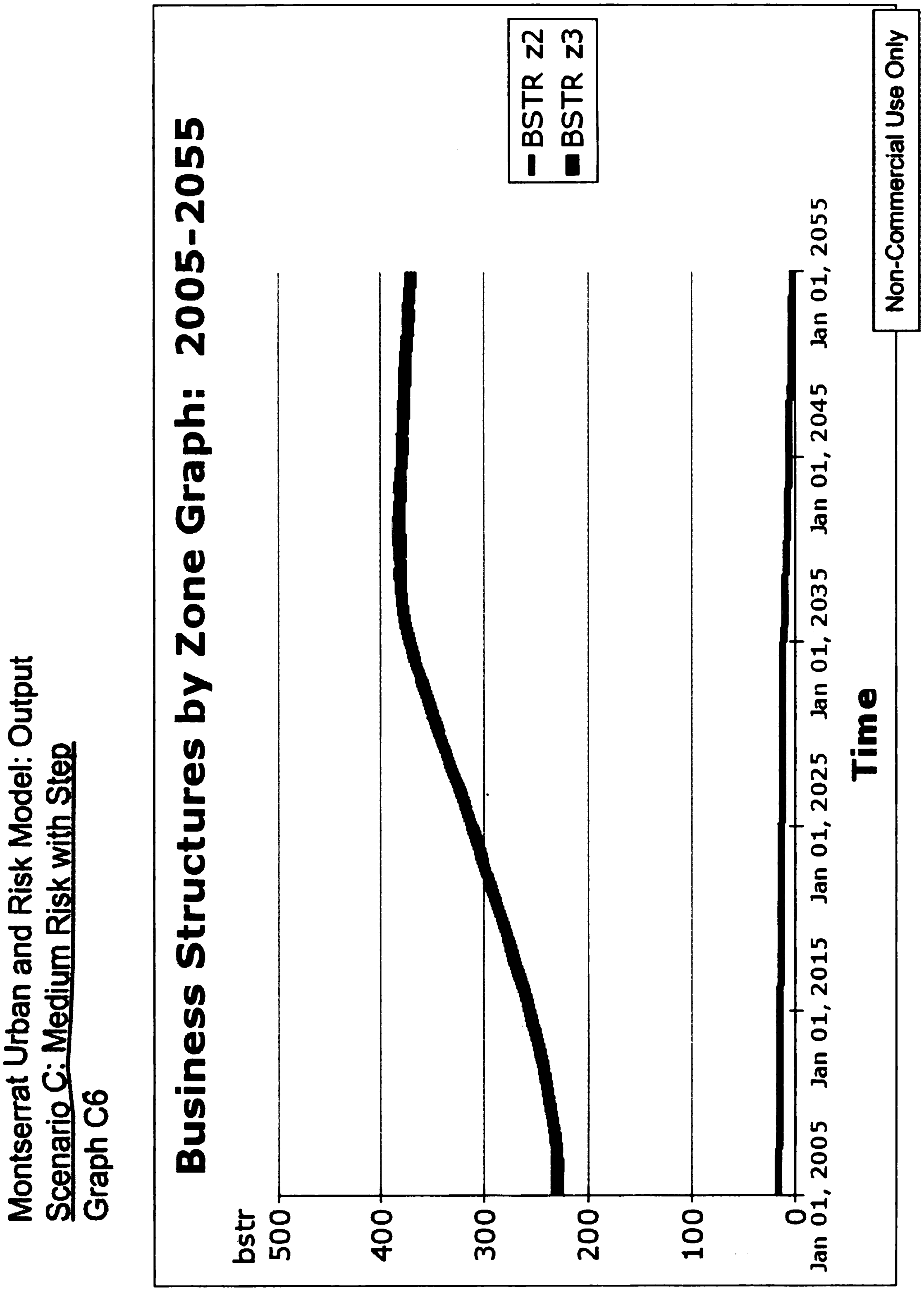


Figure 88. Model Output Graph C6

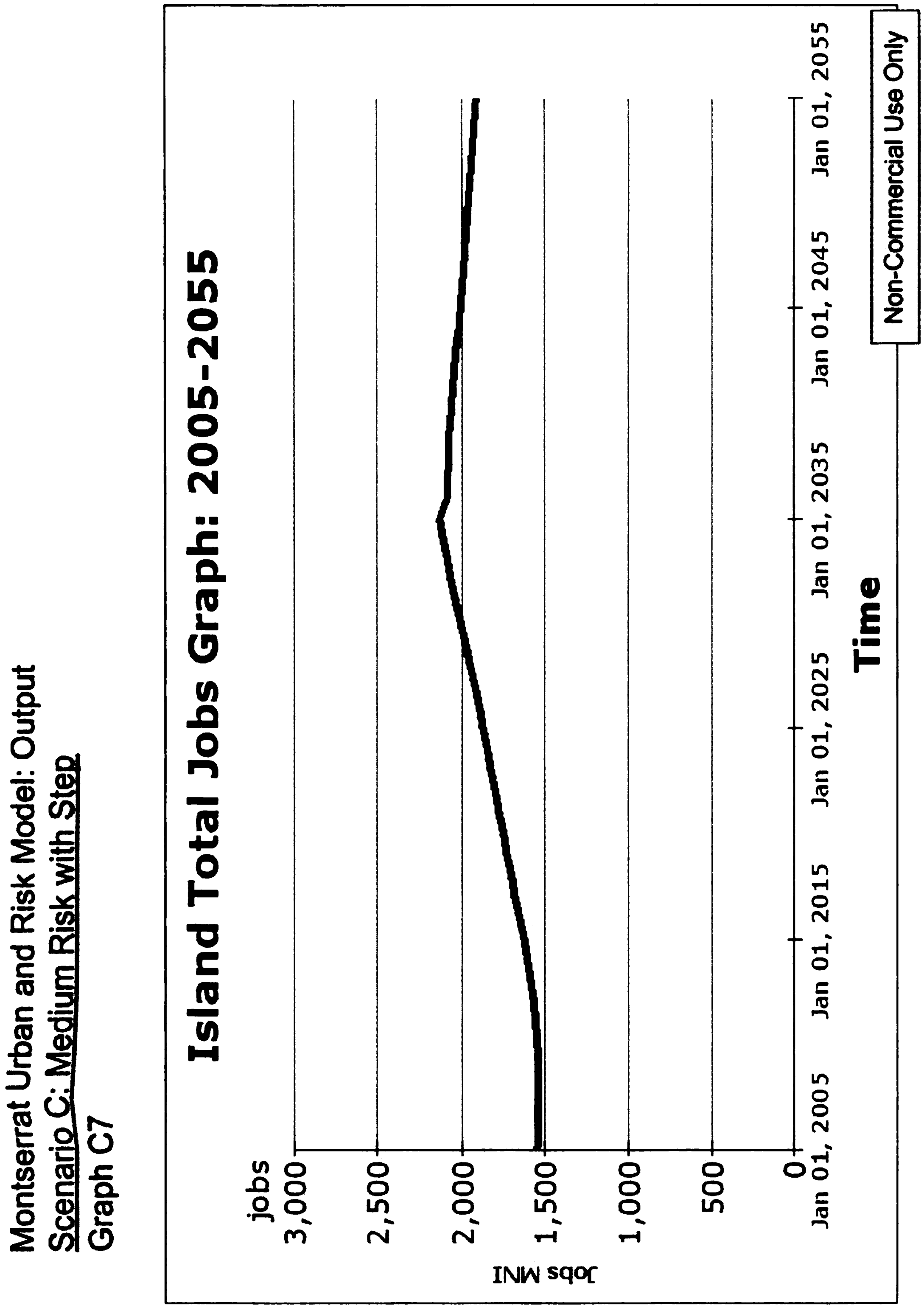


Figure 89. . Model Output Graph C7

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C8

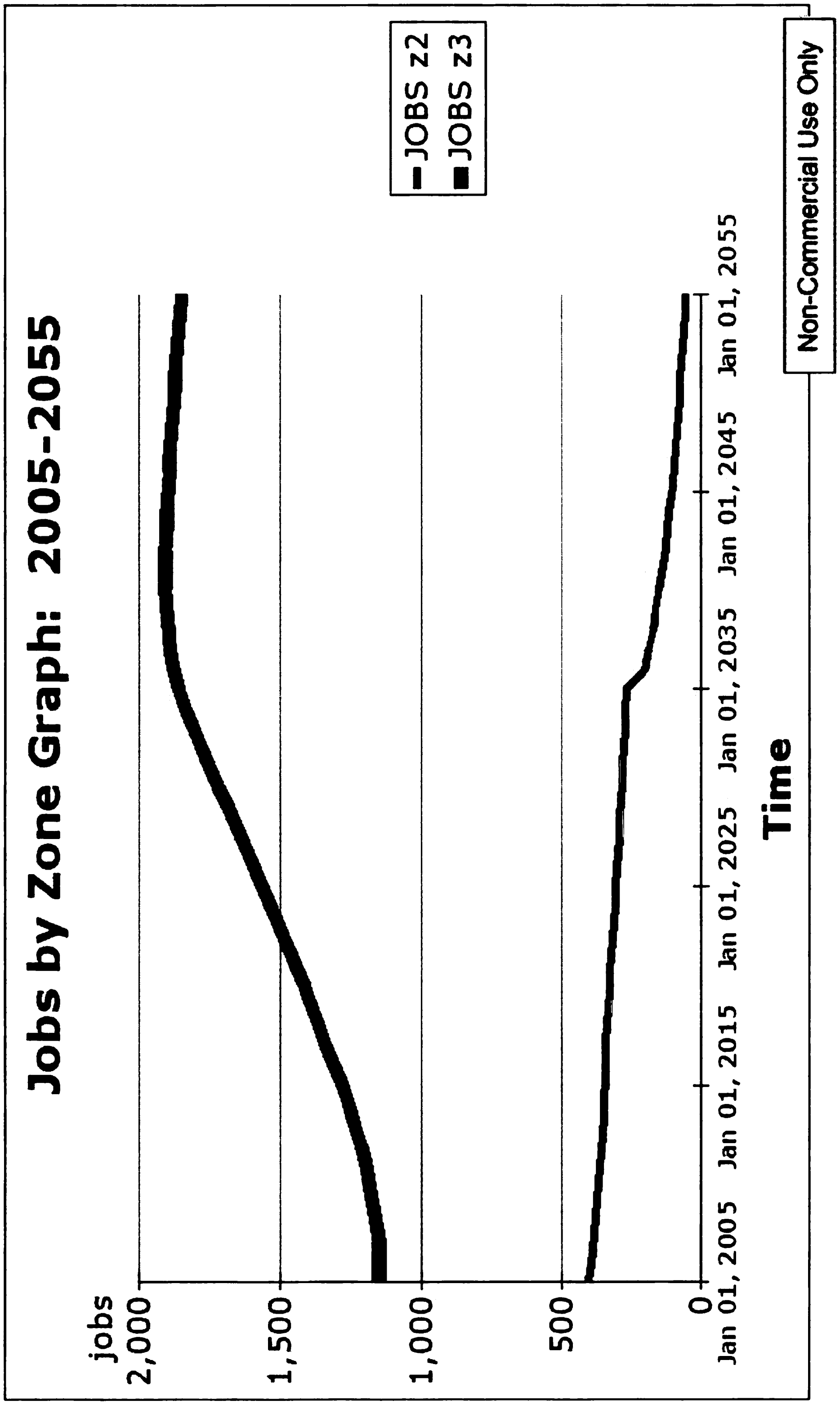


Figure 90. Model Output Graph C8

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C9

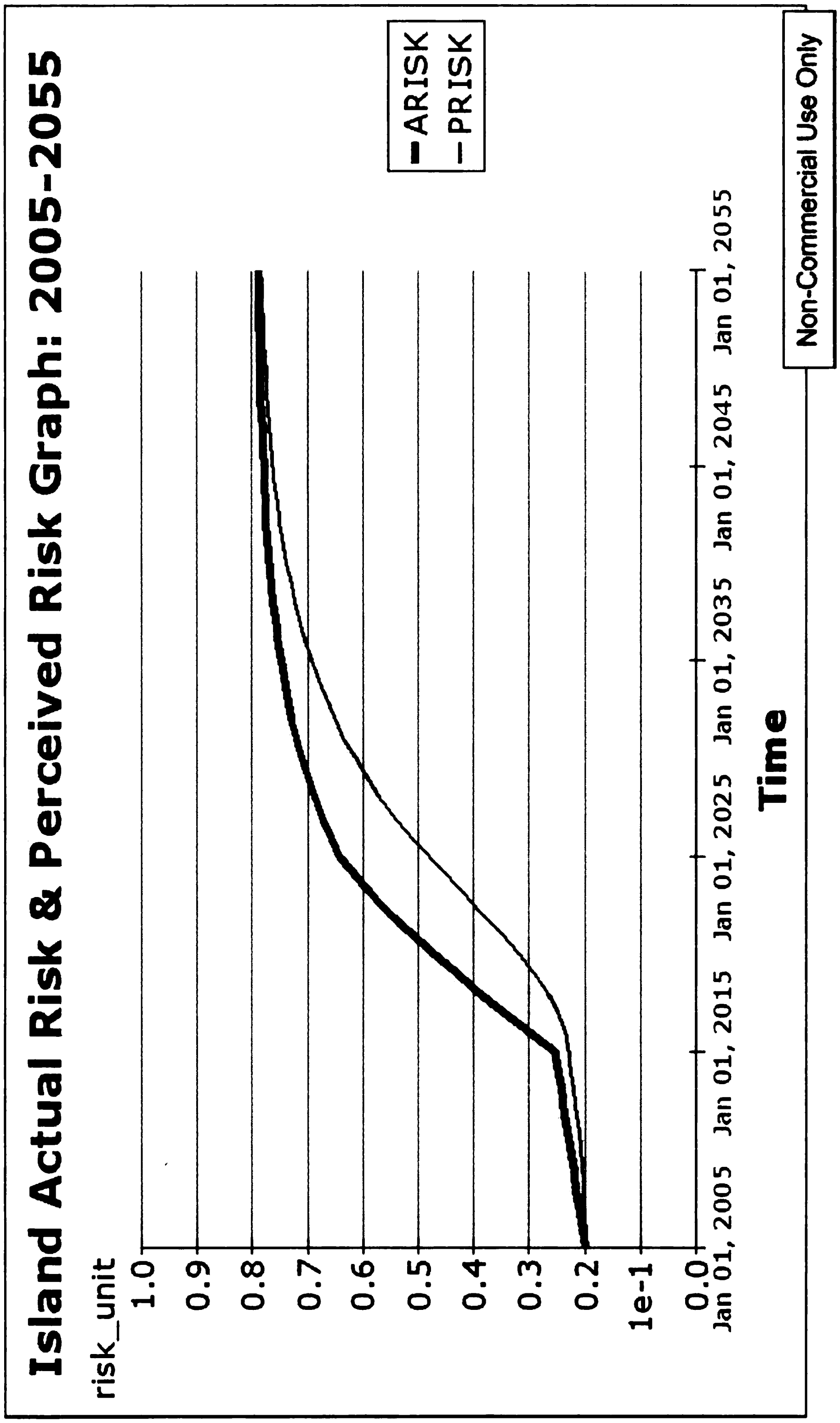


Figure 91. Model Output Graph C9

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C10

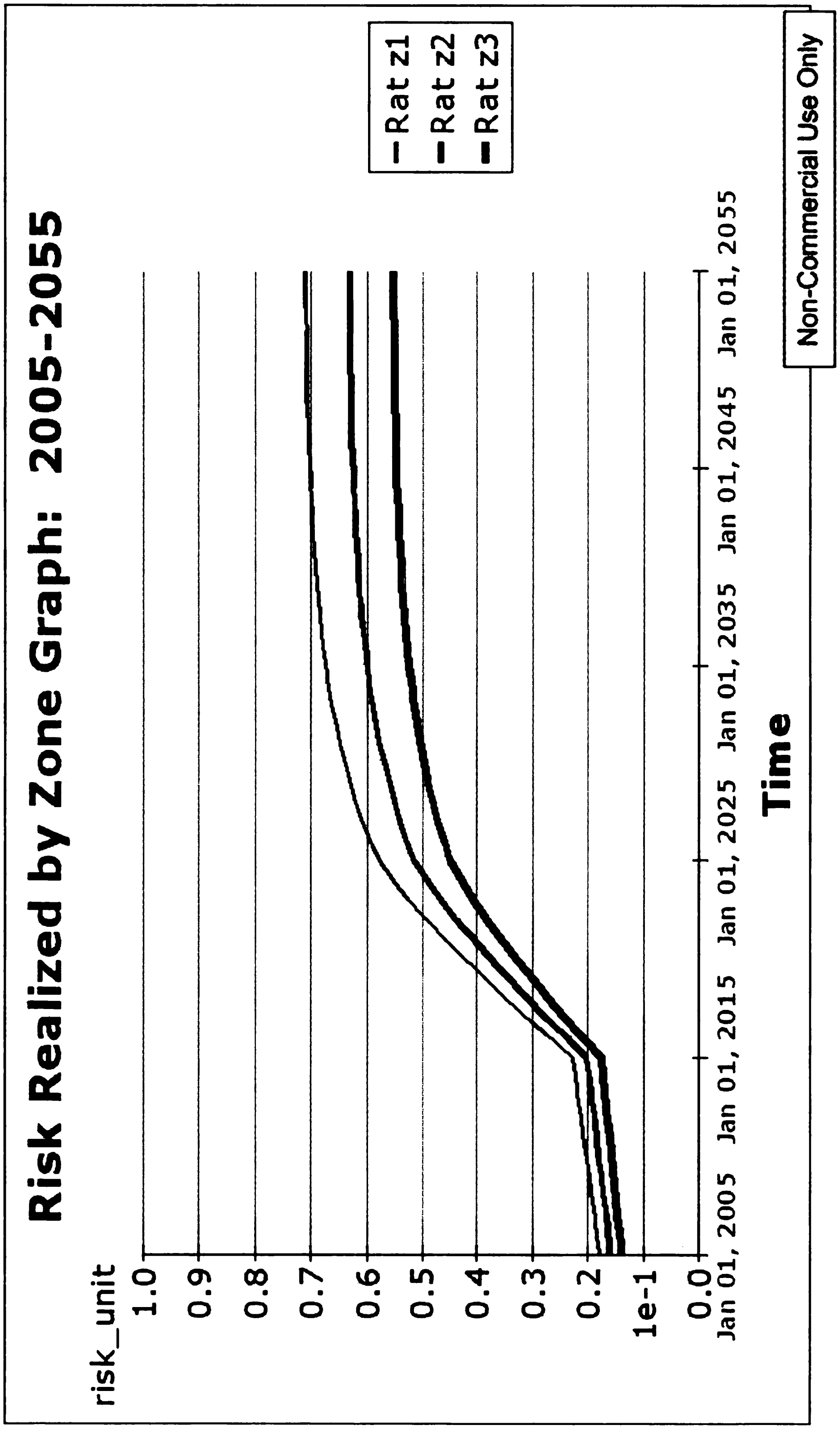


Figure 92. Model Output Graph C10

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C11

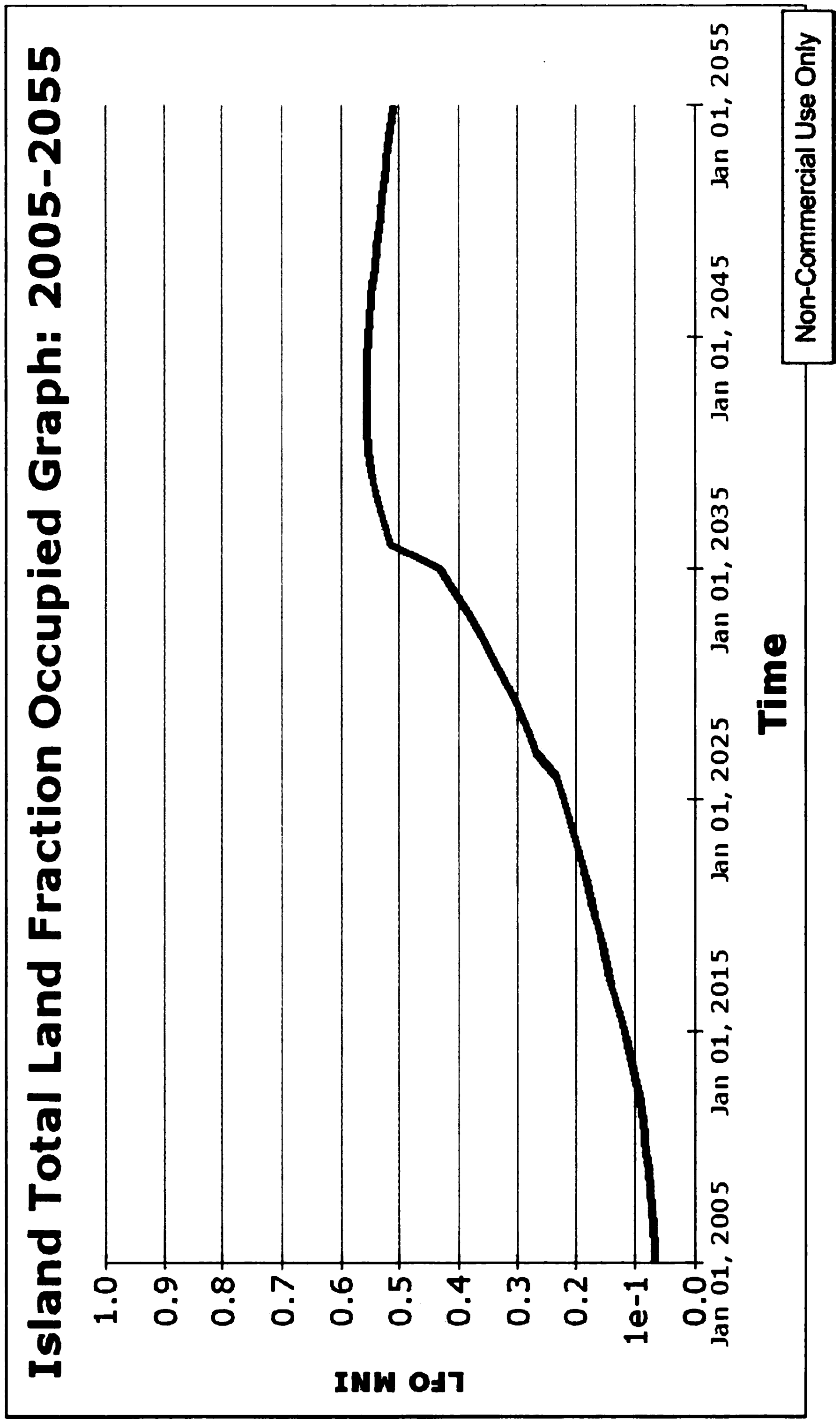


Figure 93. Model Output Graph C11

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C12

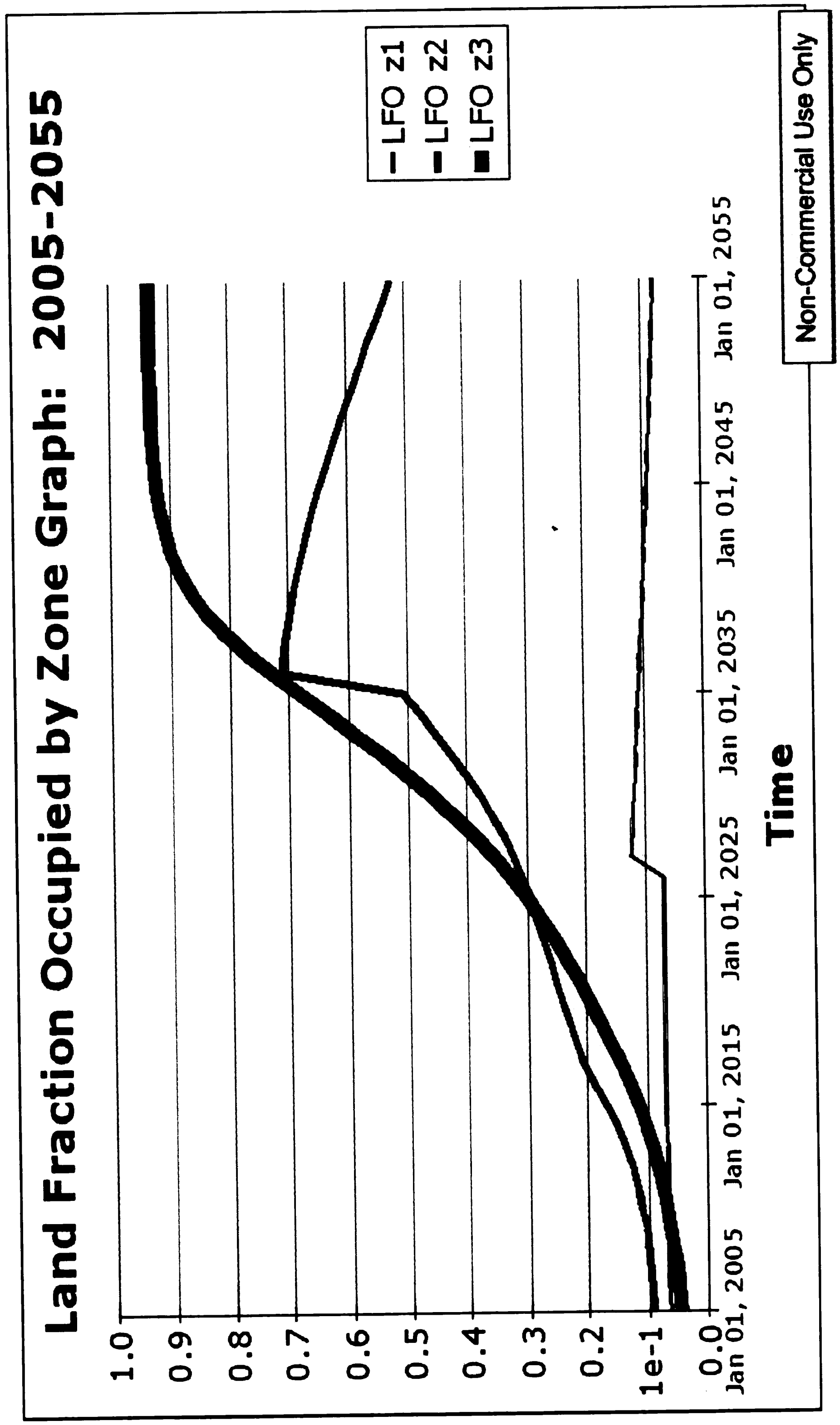


Figure 94. Model Output Graph C12

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C13

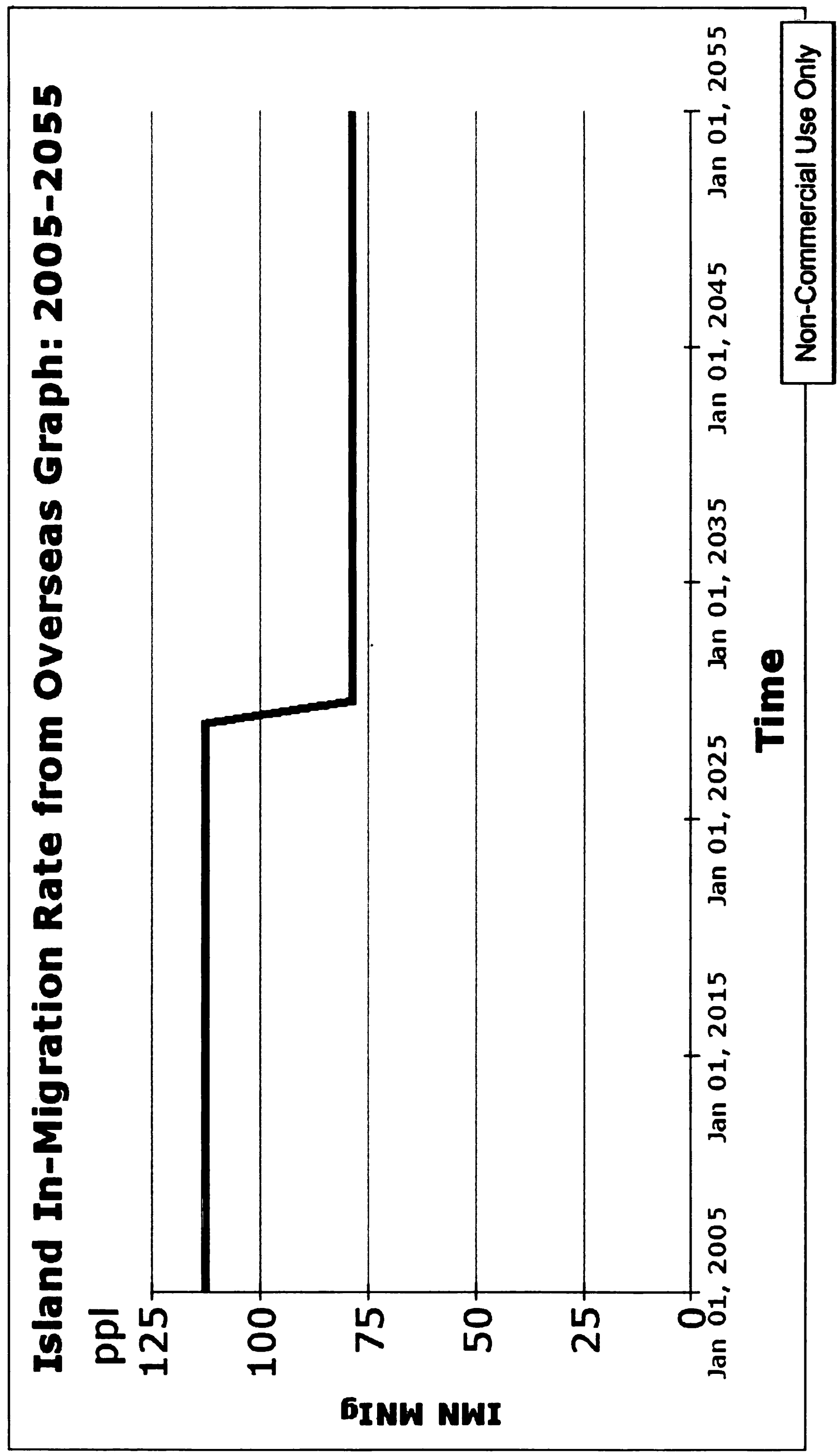


Figure 95. Model Output Graph C13

Montserrat Urban and Risk Model: Output
Scenario C: Medium Risk with Step
Graph C14

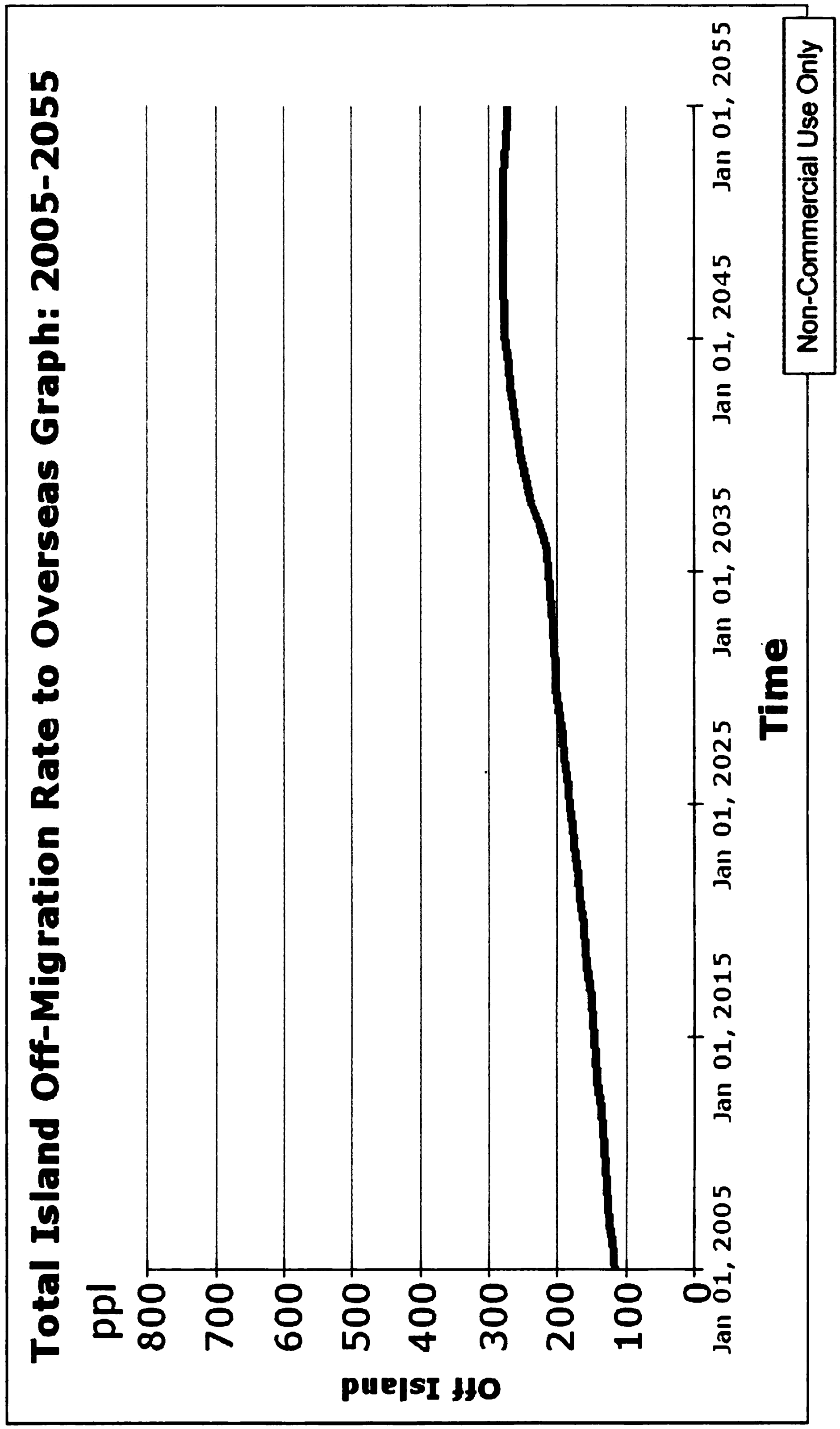


Figure 96. Model Output Graph C14

Montserrat Urban and Risk Model: Output
<u>Scenario C: Medium Risk with Step</u>
Graph C15

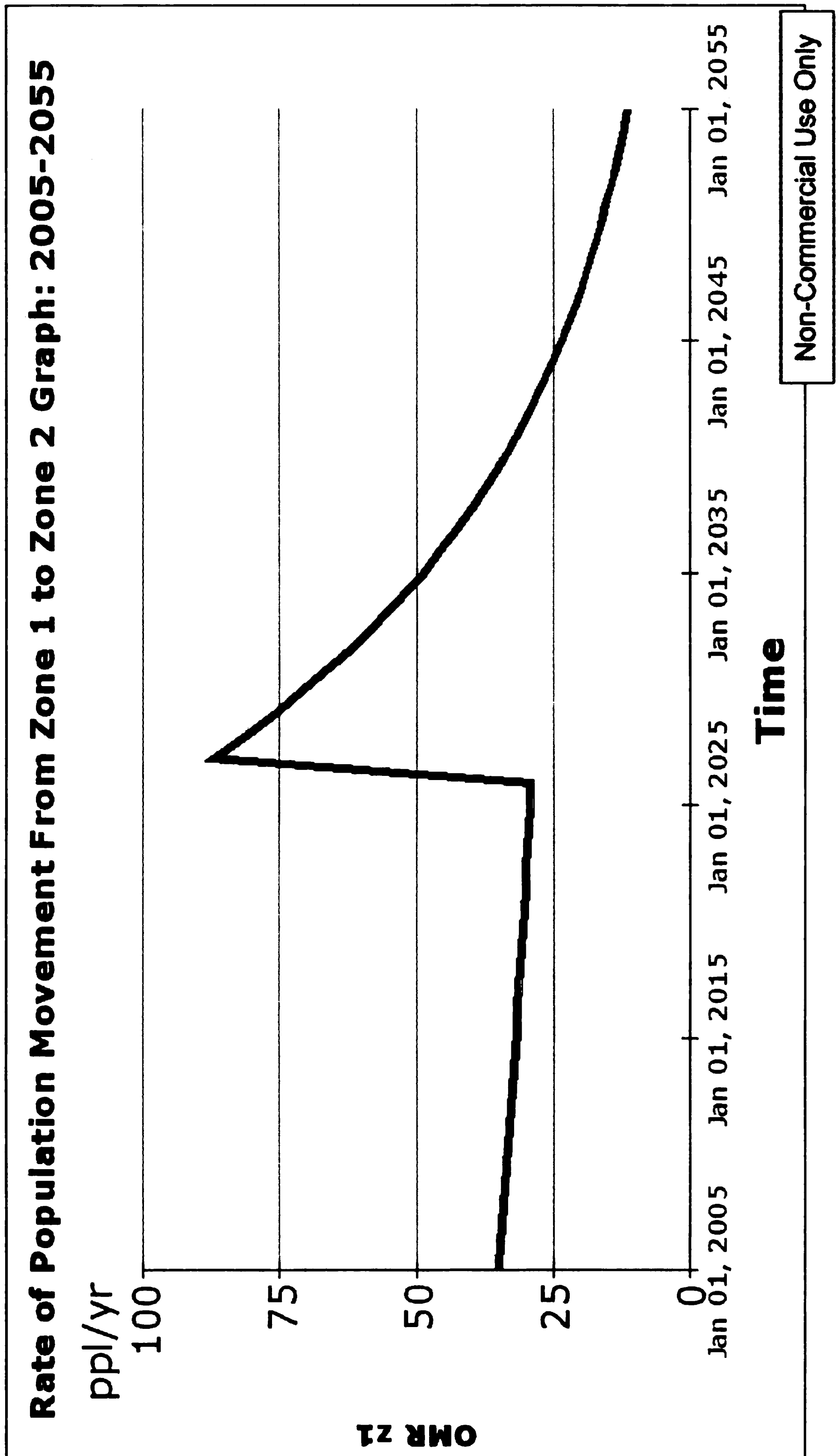


Figure 97. Model Output Graph C15

Montserrat Urban and Risk Model: Output
<u>Scenario C: Medium Risk with Step</u>
Graph C16

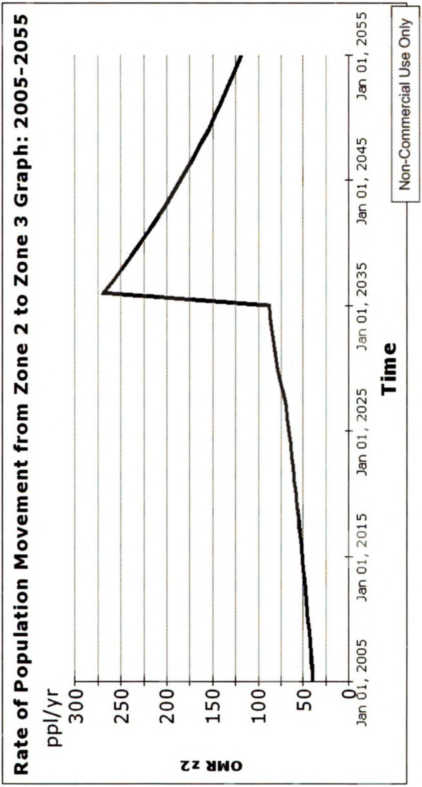


Figure 98. . Model Output Graph C16

6.5.3.2 *SCENARIO C* – Interpretation of Model Output

While the results of the simulation under *SCENARIO C* are somewhat similar to *SCENARIO B*, there are a few differences that are noticeable from altering the rate of increase in the level of risk using the step function.

Figure 94 illustrates behavior of a spike in the land fraction occupied in zone 2 (similar to Figure 78), however as the increased risk threshold impacts zone 2 at an earlier date, less construction has taken place. Therefore, even though land available for development is reduced as the volcanic activity increases, the fraction of land occupied at the time of impact is lower, which corresponds to a lower spike in land fraction occupied value.

Also as the step causes risk to reach higher levels faster, a threshold for lowering the in-migration rate is reached in approximately 30 years (see Figure 95), even with the delay in risk perception. The step in risk behavior results in population reaching a lower total level at the end date of *SCENARIO C* (see Figure 83) as compared to *SCENARIO B* (see Figure 67). These results indicate that it would be possible to model estimated population loss, and subsequent effects on housing, businesses, etc by various types of volcano behaviors.

6.5.4 *SCENARIO D* – High Risk

SCENARIO D is named high risk.

SCENARIO D represents a high volcanic risk where over the 50 year period risk increases by five times. This scenario represents a gradual build up of extreme volcanic activity with high levels of risk being reached quickly (see Figure 107). Under this high risk scenario, risk increases to a level where the island's population declines. The population eventually declines to a level below the scenario's initial population level (see Figure 99). This scenario represents one of the worst cases where risk will eventually depopulate the island.

6.5.4.1 *SCENARIO D* – Model Output

The following Figures 99-114 depict the results of *SCENARIO D*.

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D1

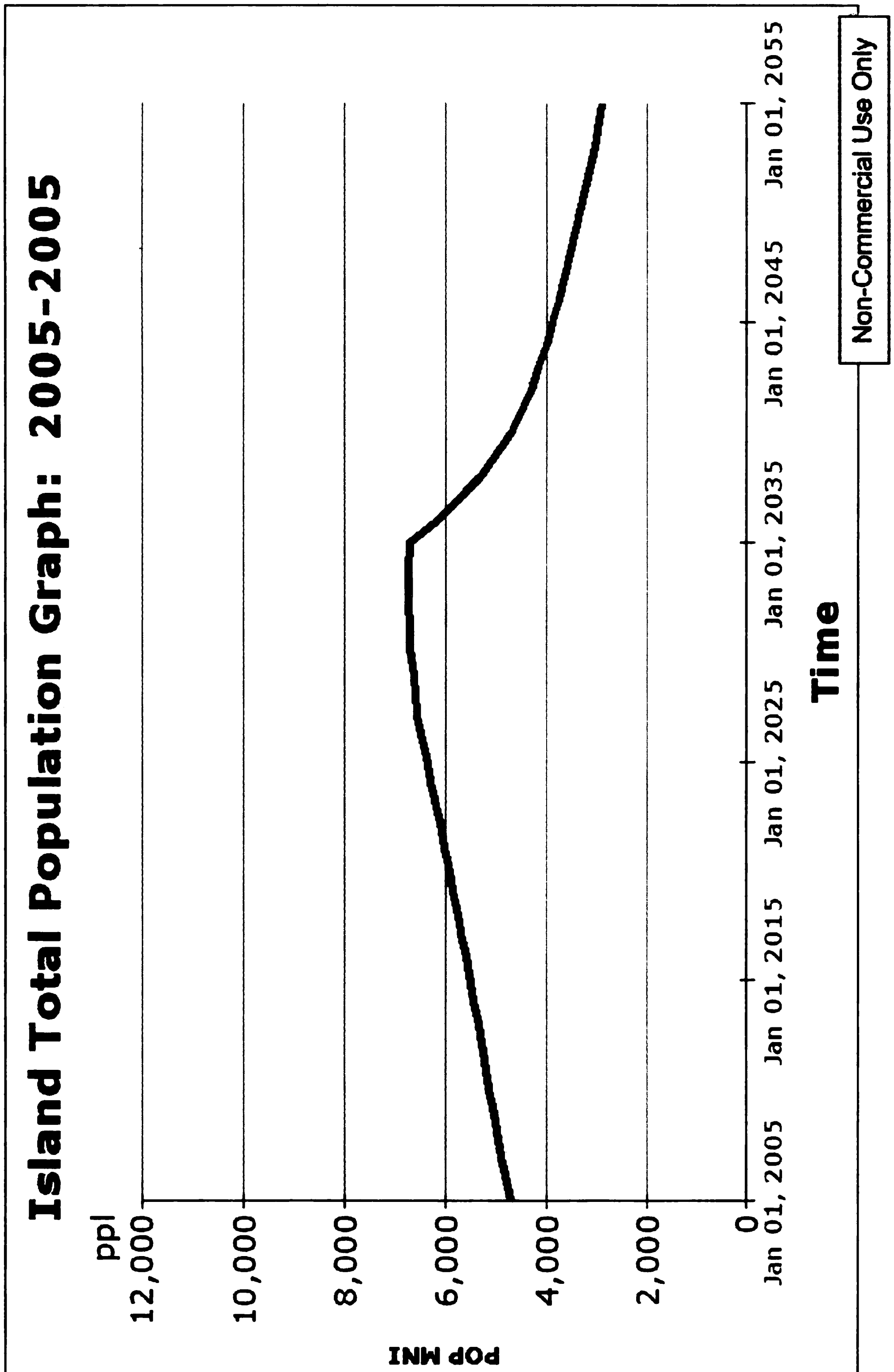


Figure 99. Model Output Graph D1

Montserrat Urban and Risk Model: Output
<u>Scenario D: High Risk</u>
Graph D2

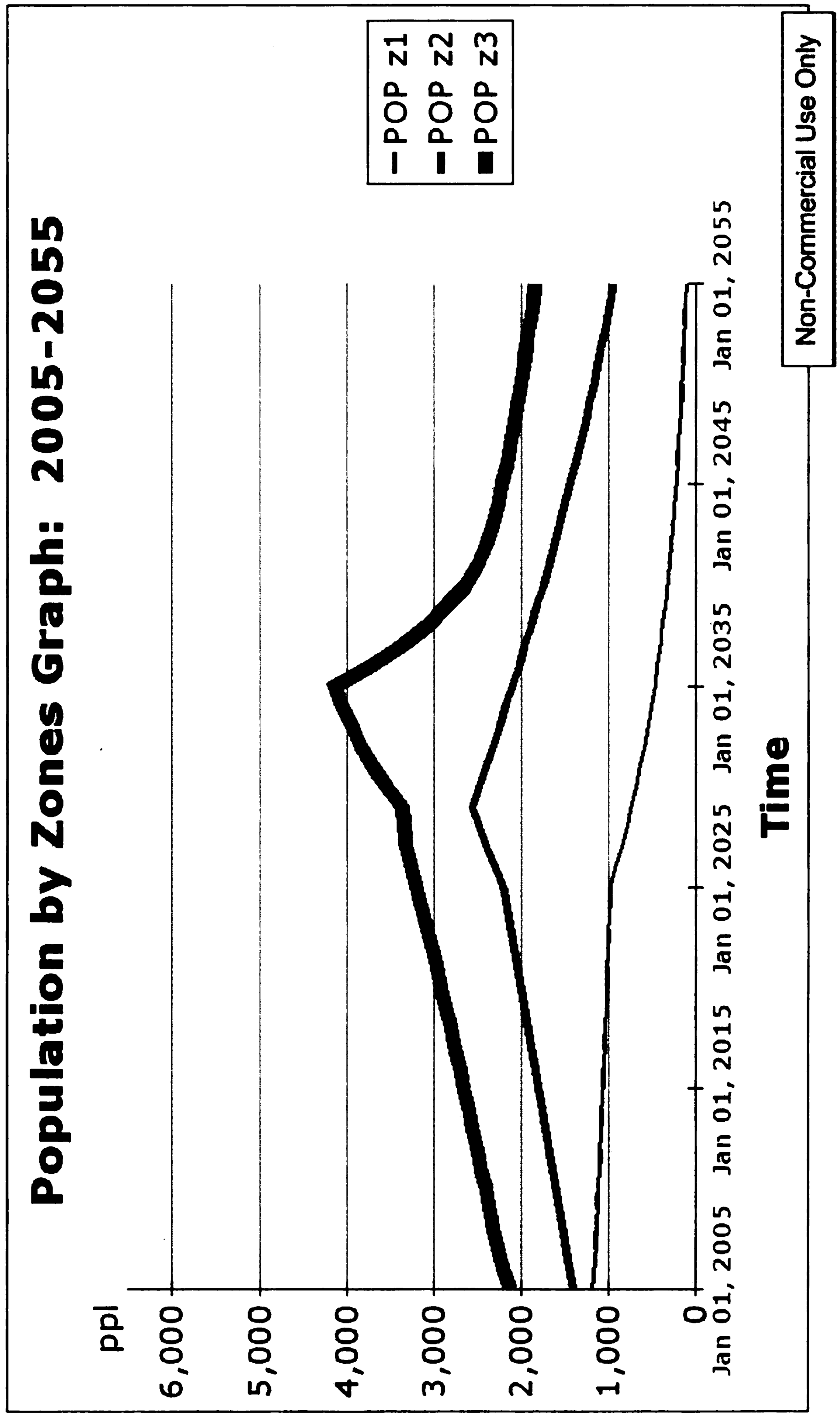


Figure 100. Model Output Graph D2

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D3

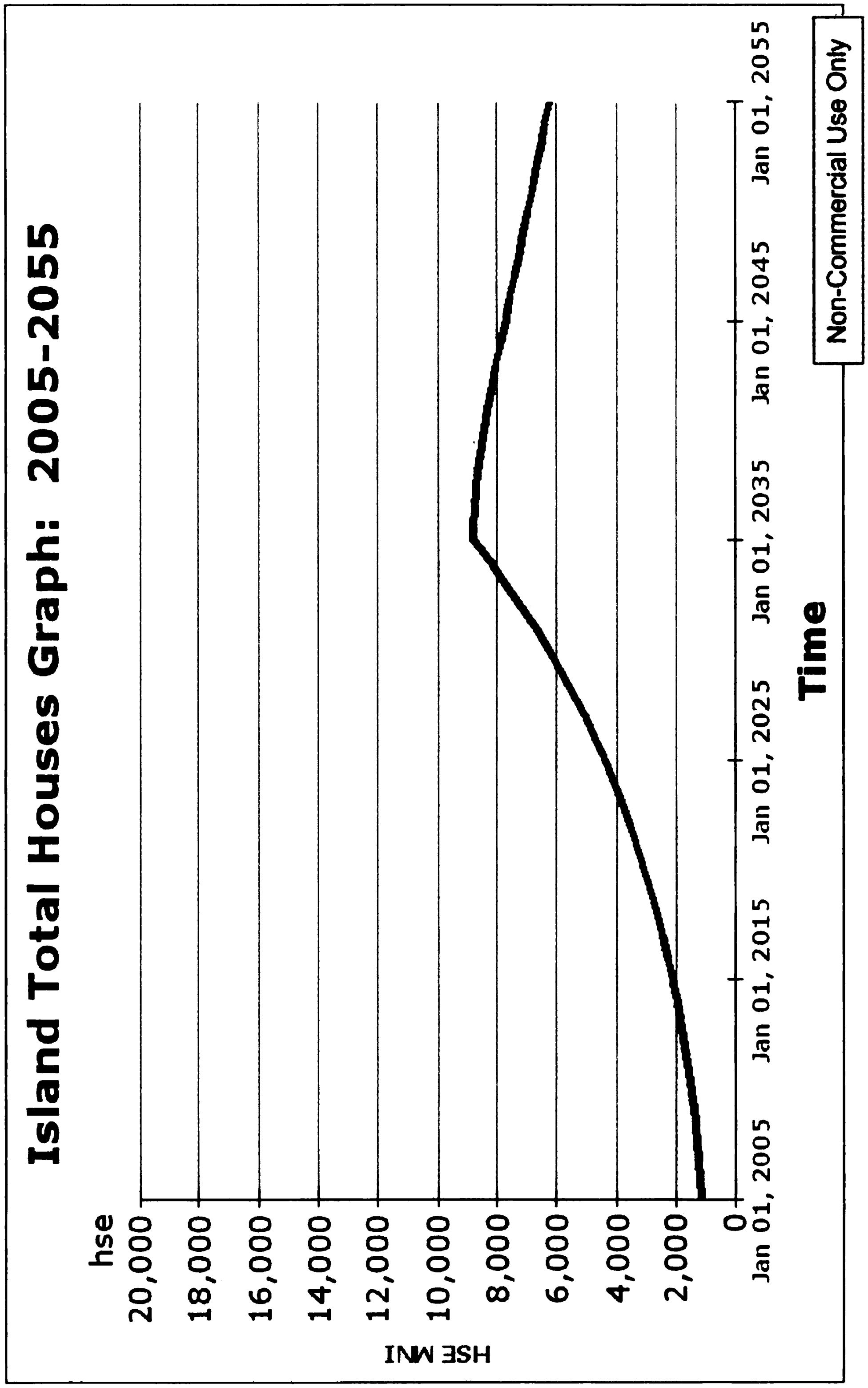


Figure 101. Model Output Graph D3

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D4

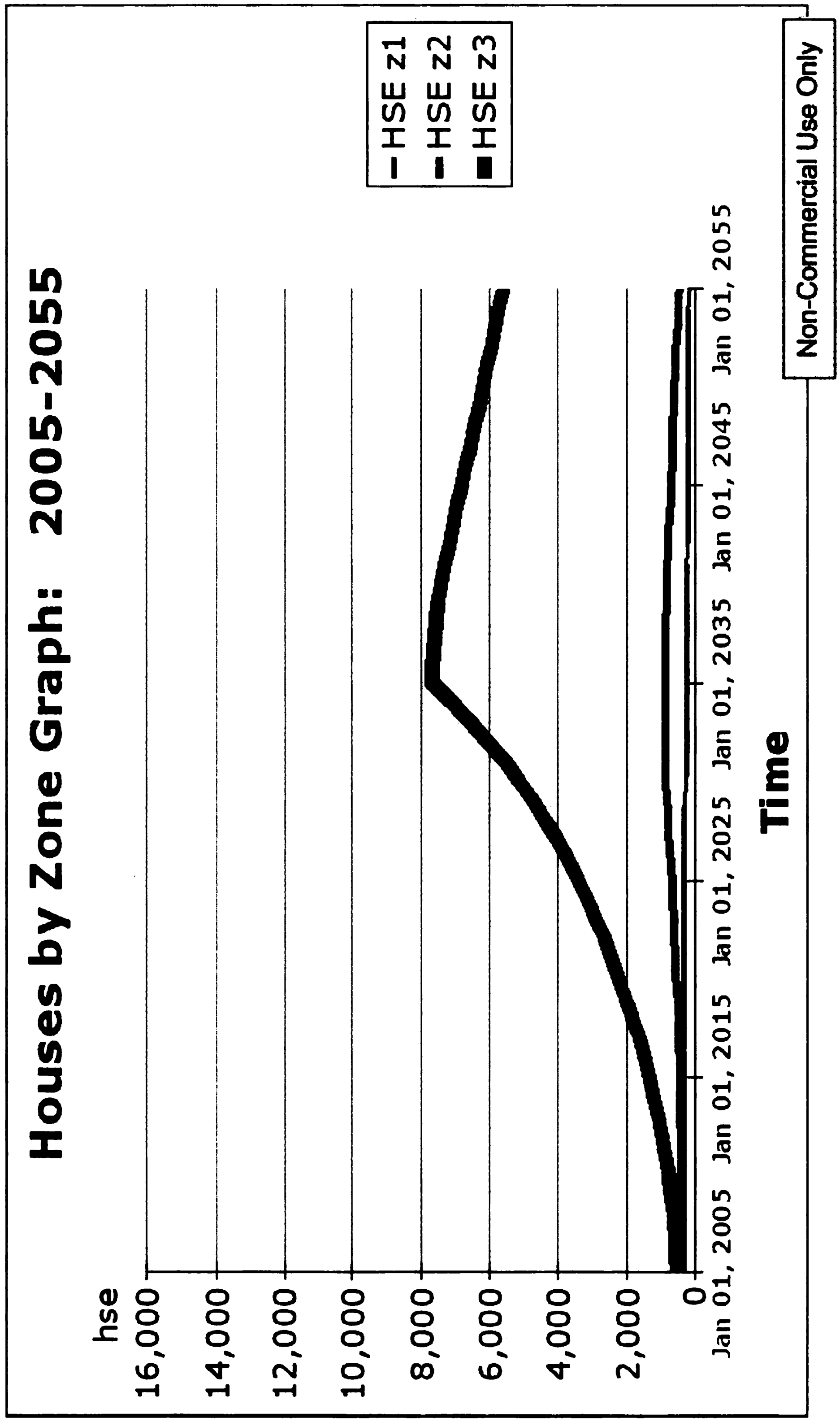


Figure 102. Model Output Graph D4

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D5

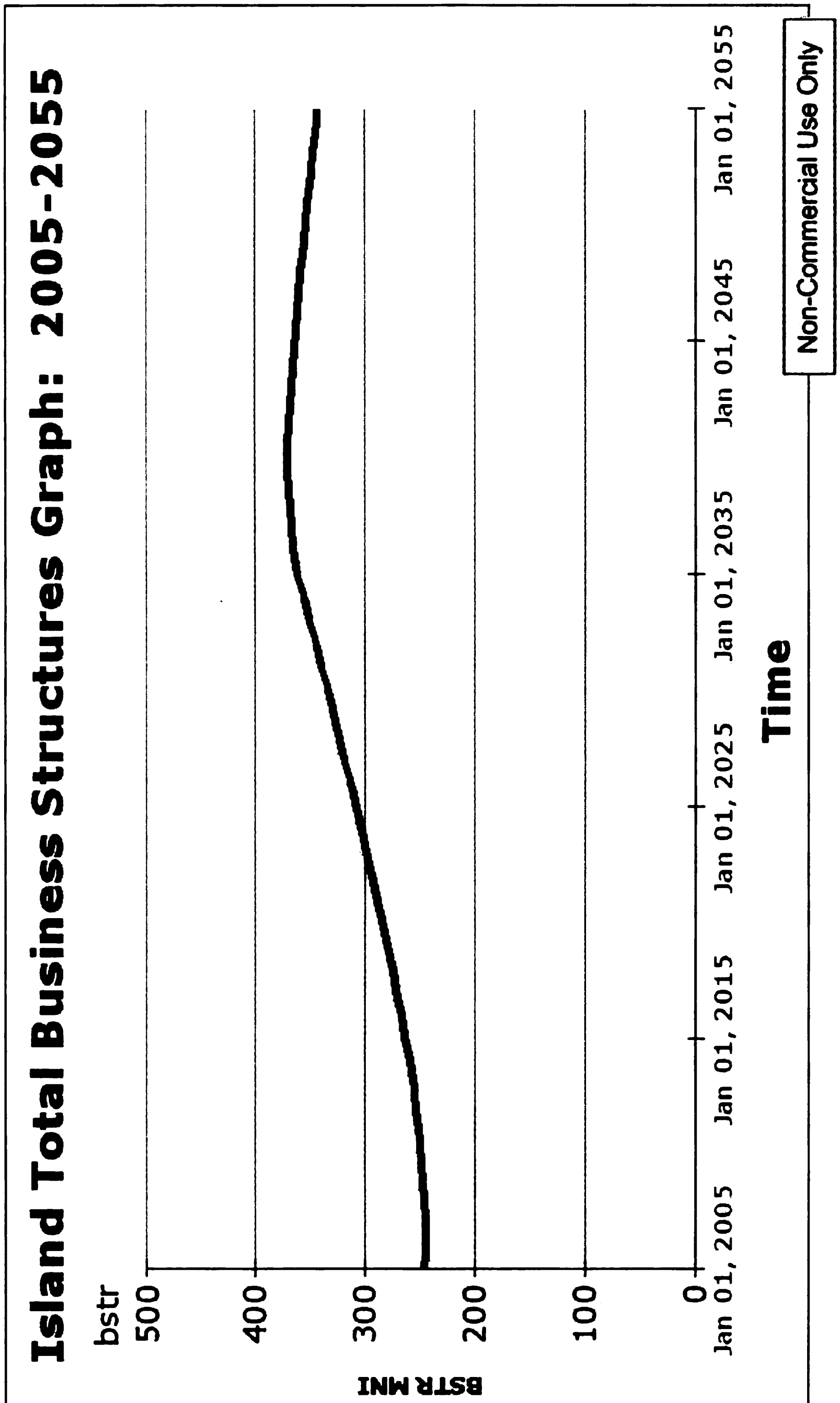


Figure 103. Model Output Graph D5

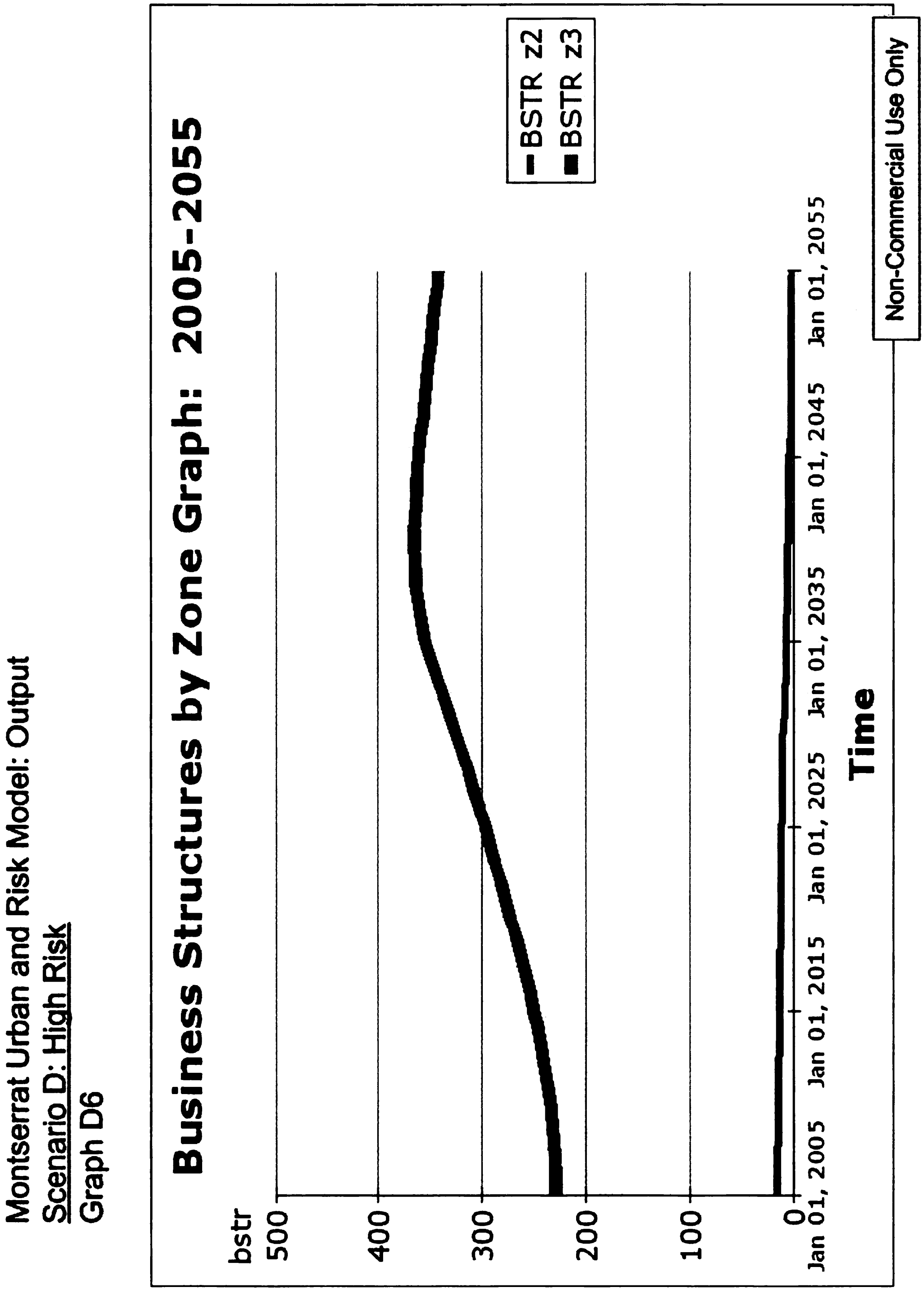


Figure 104. Model Output Graph D6

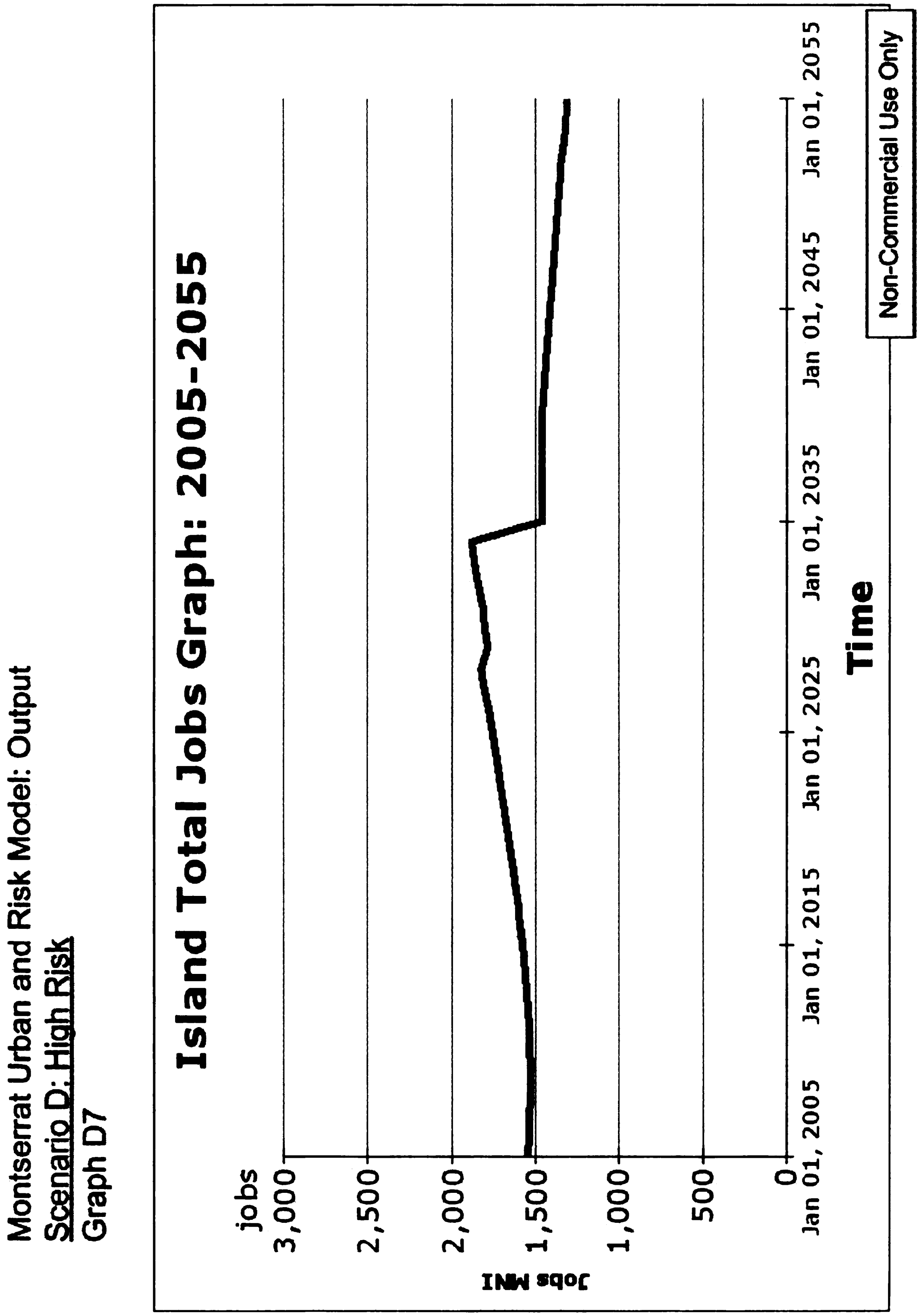


Figure 105. . Model Output Graph D7

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D8

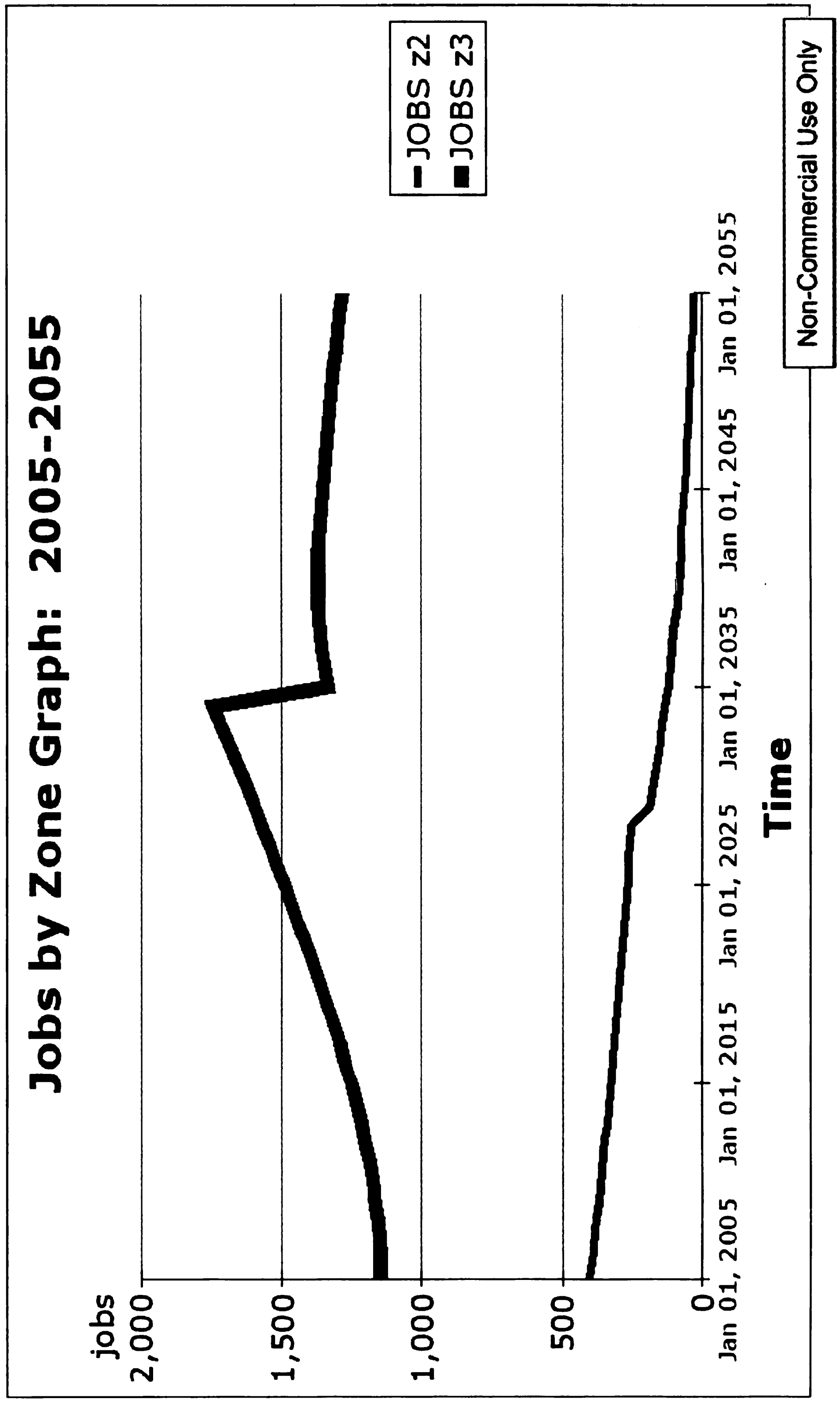


Figure 106. Model Output Graph D8

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D9

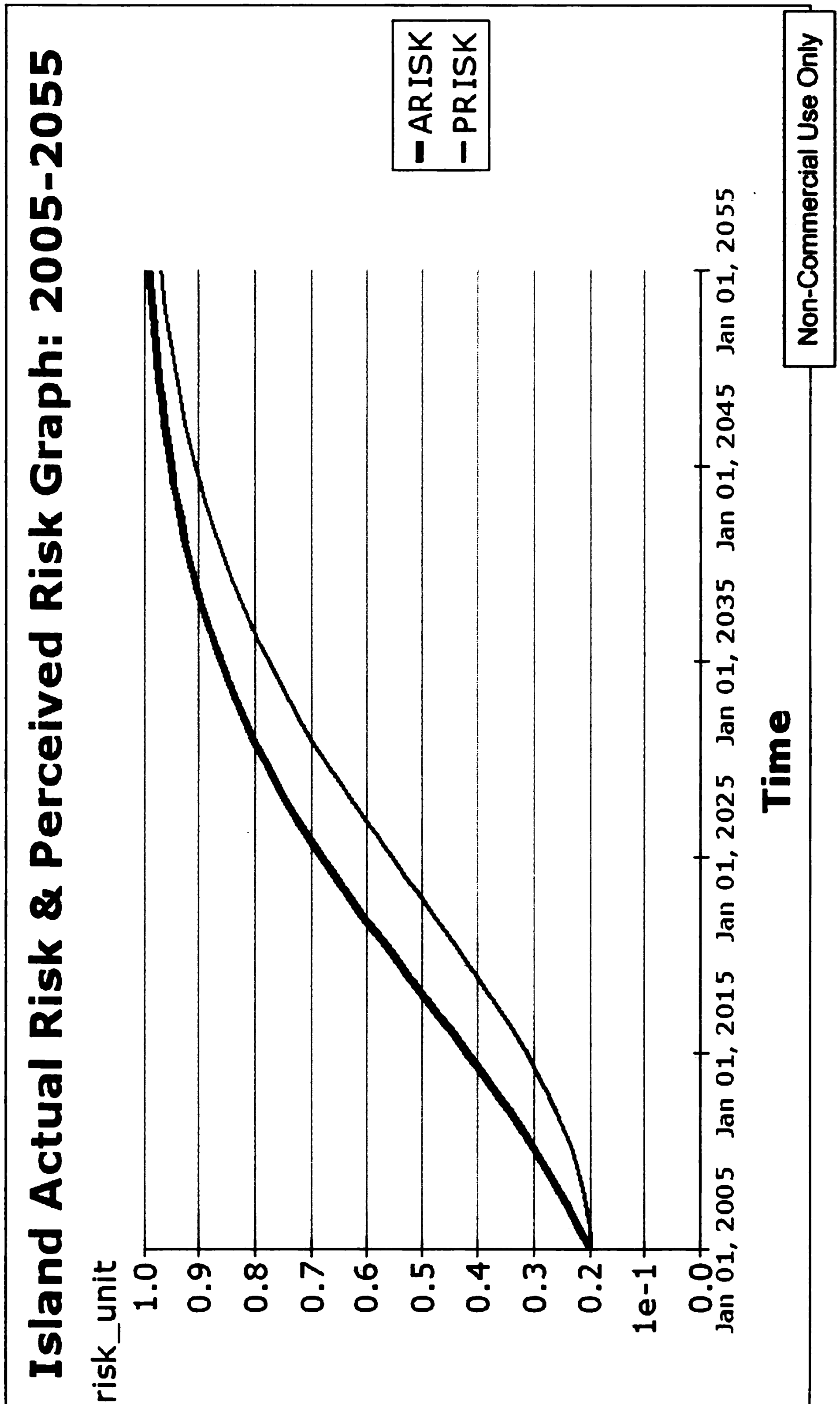


Figure 107 . Model Output Graph D9

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D10

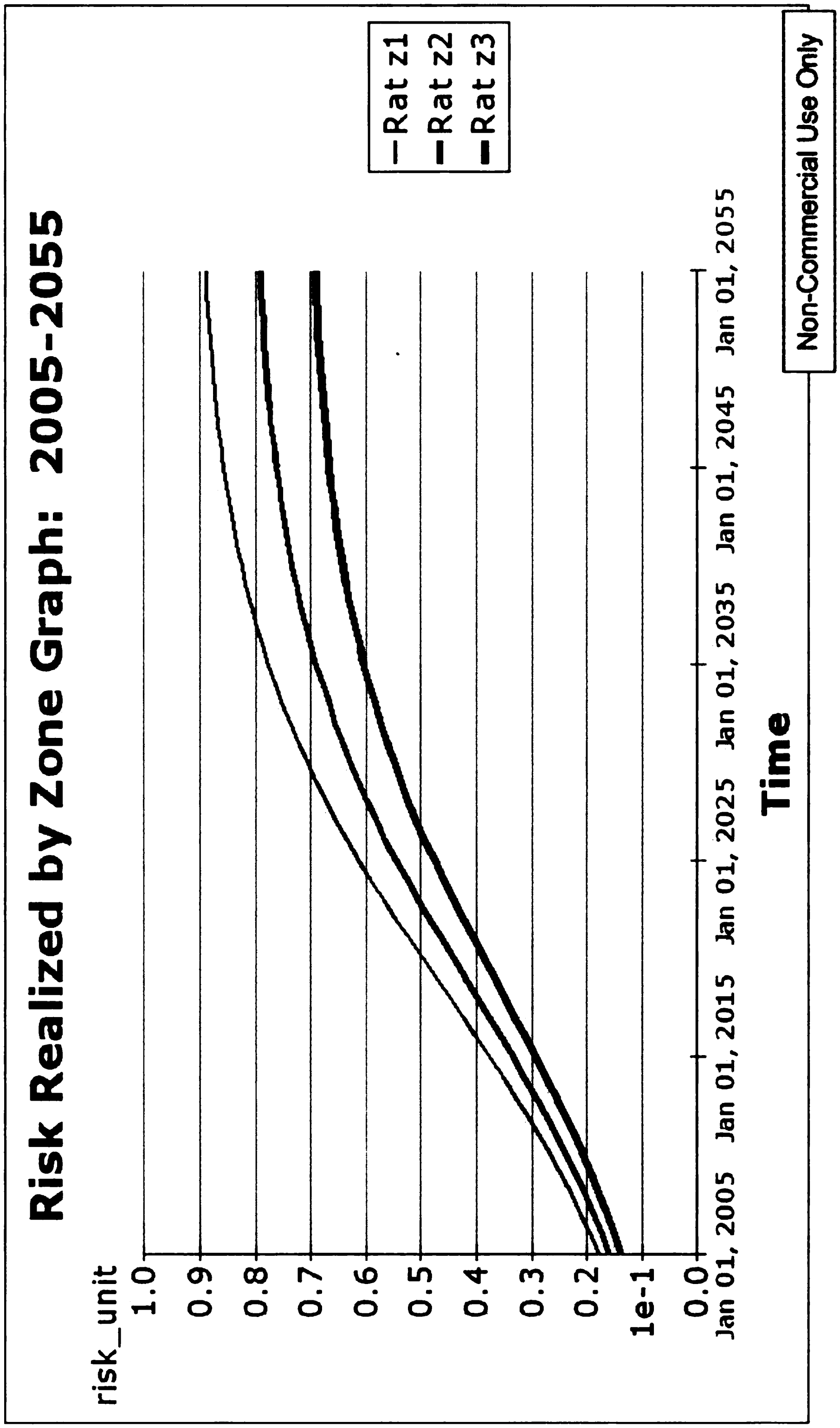


Figure 108. Model Output Graph D10

Montserrat Urban and Risk Model: Output

<u>Scenario D: High Risk</u>

Graph D11

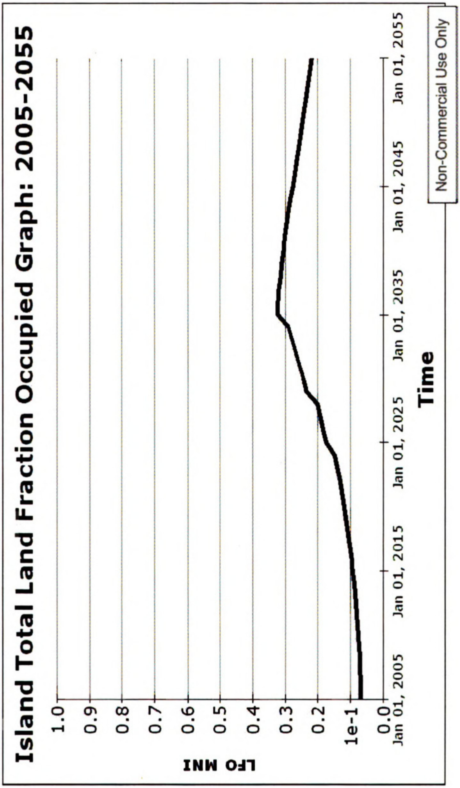


Figure 109. . Model Output Graph D11

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D12

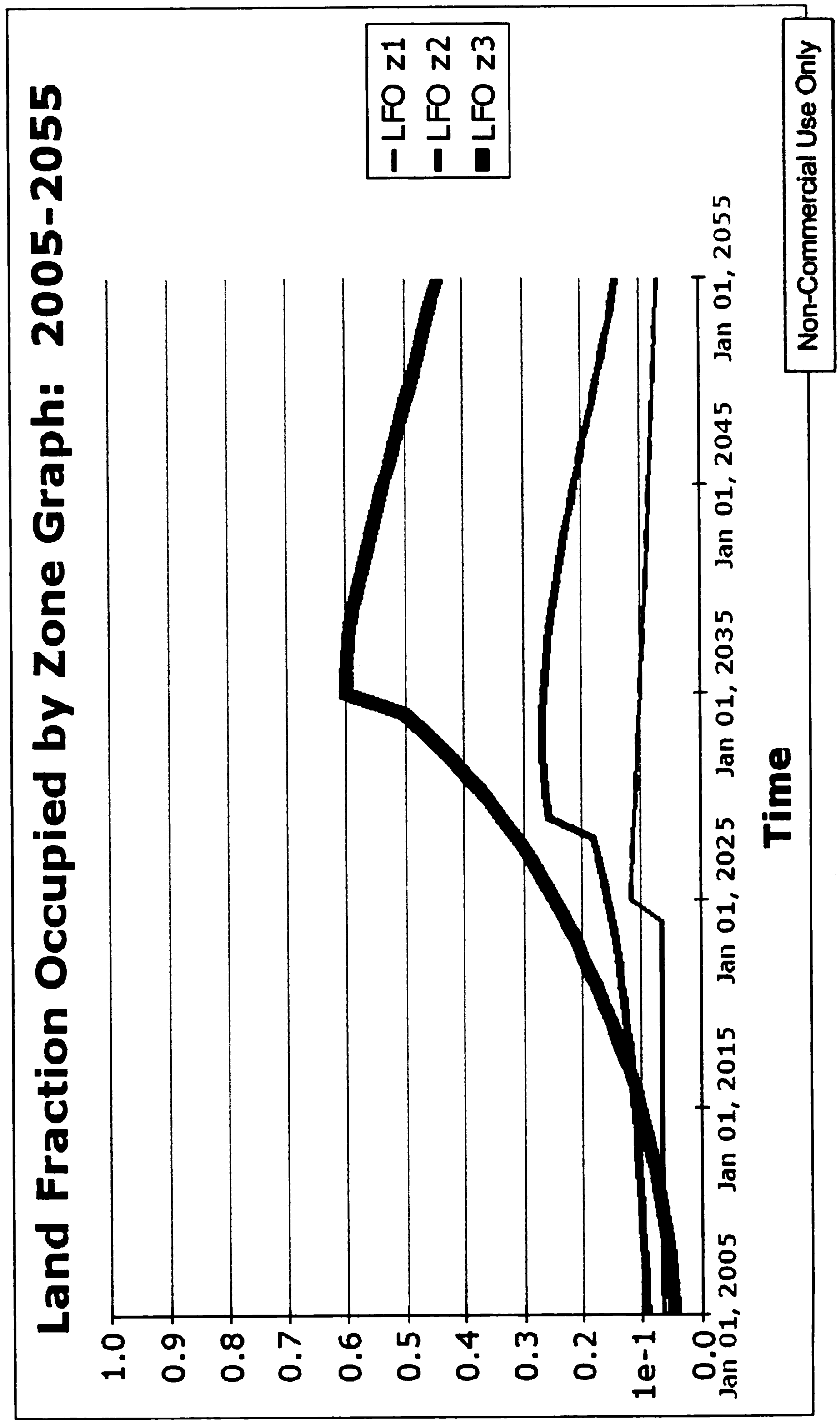


Figure 110. Model Output Graph D12

Montserrat Urban and Risk Model: Output
Scenario D: High Risk
Graph D13

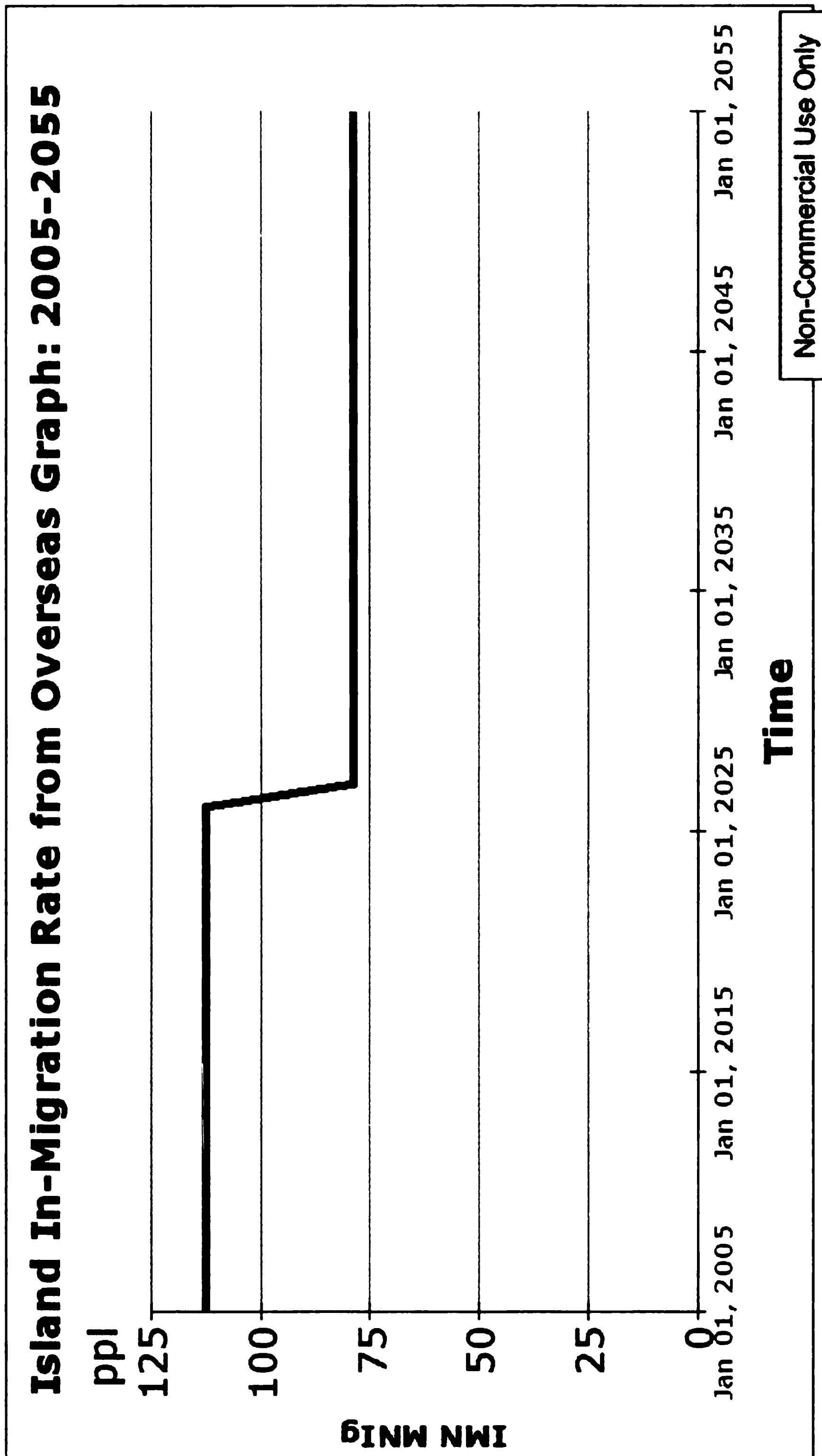


Figure 111. Model Output Graph D13

Montserrat Urban and Risk Model: Output

Scenario D: High Risk

Graph D14

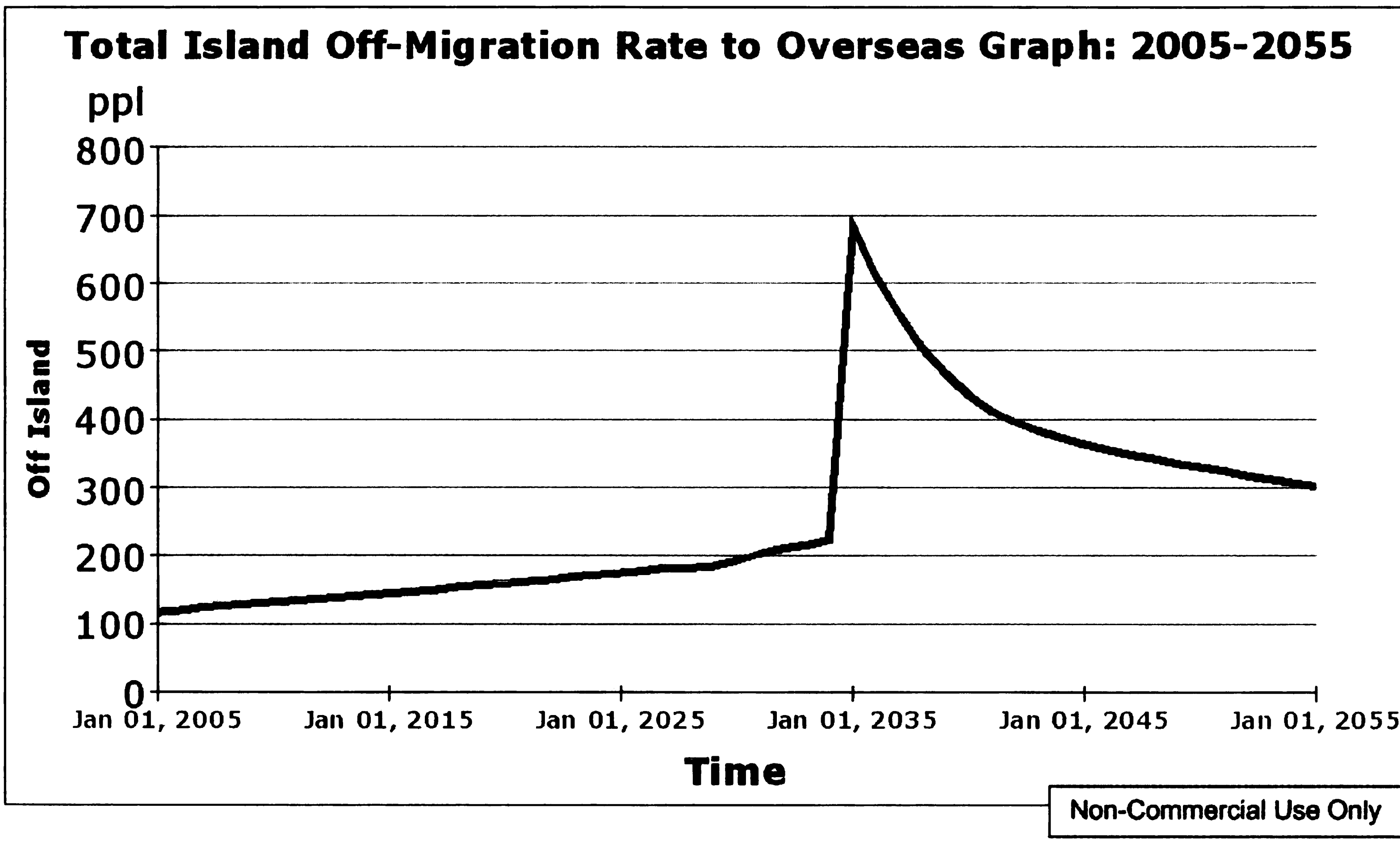


Figure 112. Model Output Graph D14

Montserrat Urban and Risk Model: Output

Scenario D: High Risk

Graph D15

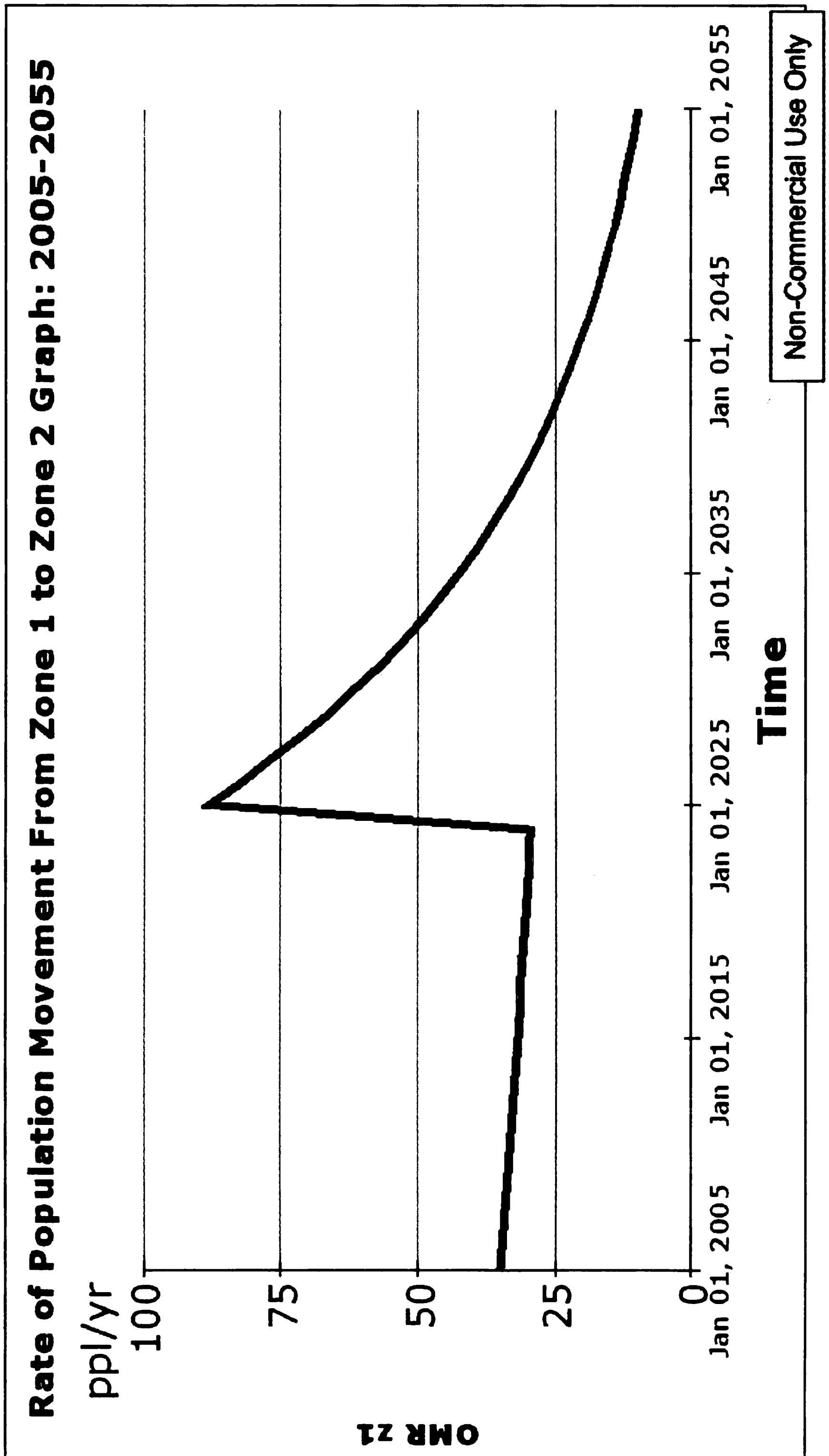


Figure 113.. Model Output Graph D15

Montserrat Urban and Risk Model: Output
<u>Scenario D: High Risk</u>
Graph D16

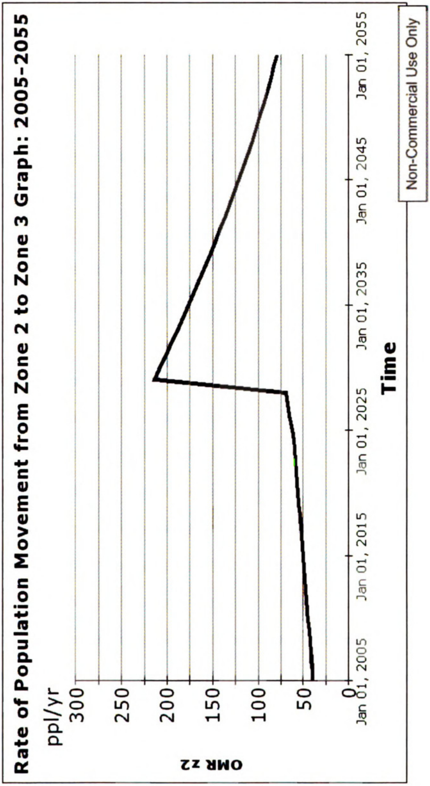


Figure 114. . Model Output Graph D16

6.5.4.2 *SCENARIO D* – Interpretations of Model Output

A highlight of *SCENARIO D* is the decline in population (see Figure 99) and housing (see Figure 101).

Regarding the impact on business structures, while the risk has the least impact in zone 3, where a majority of the business structures are located, the decline in the number of business structures is not as drastic (see Figure 103 and Figure 104). The risks in *SCENARIO D* also impact jobs (see Figure 105) as thresholds are passed (as the risk level passes 0.6) where some of the employment capacity has to be diverted to emergency activities.

If any benefit of the high risk scenario can be determined for Montserrat, that benefit will have to be realized by future generations. Figure 109 indicates that at the end date for *SCENARIO D* the land fraction occupied is only at 22%. Once the volcano goes into a state of repose and the risk becomes lower future generations may be able to take advantage of the developable land remaining once the risk subsidies.

A major difference in this high risk scenario as compared to the lower risks scenarios is represented in Figure 112, where both the increased risk and population migration from other zones cause a spike of over two times for off-migration from the island. This mass evacuation would take place around 2035. One can track when risk overwhelms the capacity of zones 1, zone 2, and zone 3, by looking at Figure 113, Figure 114, and Figure 112 respectively. Risk pushes population out of zone 1 around 2020, out of zone 2 around 2028, and then culminates in pushing people off the island in 2035. At that point the time, population growth ends and the island's population starts to decline (see Figure 251).

CHAPTER SEVEN

DISCUSSION OF ANALYTICAL RESULTS

7.1 Discussion of Analytical Results

This chapter comments on the results of the model's output. Interpretations are provided and model behavior is related to real life situations on Montserrat. Seven main interpretations are suggested, drawing from cross-comparisons of the model's output under the four scenarios.

A main conclusion to be drawn is that it is questionable whether Montserrat can reach a population of 10,000 persons. This author suggests that a range of 6,500 to 7,500 persons may be more appropriate for the island. A key finding is the model variable of land fraction occupied is a main limiting factor for future redevelopment of the island. Also, an increase in risk will not necessarily lead to a decline in population. While this may seem counterintuitive, model results have shown this situation to be the case. The model also depicts situations under certain scenarios where hundreds of people flow from one zone to another zone as a result of increased risk. If such movements are realized, the effects may unravel the social fabric of the island. The model also would have the ability absorb a shock of refugees being sent back to the island, however their return may result in increased pressures for off-migration. In the model, risk perception acts as a delay (or smoothing) as related to the actual risk. However, as risk perception delays the impacts of risk, it does not allow for the inevitable to be avoided. Finally, the model indicated that a dangerous trend may be in its formative stages where the safest zones are filling in to the point that in the future, a counter-reaction may take place where people begin to move closer to the volcano (into higher risk zones) as a response to crowding.

7.2 Is Montserrat's Goal of 10,000 People Feasible?

This study is based on the question: "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 people feasible, given a situation of development constraints and continued risk?" Based on assumptions, limitations, and findings from this study, this author would suggest that it is unlikely that the 10,000 persons goal is feasible. The modeling in the study indicates that a goal in the range of 6,500 to 7,500 persons may be more realistic. In making this prediction, this author has had the advantage looking back at the first phases of Montserrat's disaster recovery, and the benefit of being removed from the day-to-day reality of coping with the crisis.

When this goal was stated in 1999, the beginning phases of reconstruction were underway. Government officials working on the Montserrat crisis (who had responsibilities involving both planning for the future and coping with the present) would have had difficulty in finding the time to engage in time-consuming modeling efforts. In fact, they probably could not justify such activities, given the scope of the immediate needs present. As a result, planning projections were made with the best available information at that point in time, and in 1999 that information pointed to a population of 10,000 as a reasonable recovery goal.

That being said, we can now look at what the modeling efforts in this study have indicated concerning the 10,000 persons goal. In *SCENARIO A,* only when risk was set at a low value of 0.2 and held constant throughout the simulation (see Figure 59), the goal was reached. However, in the real world, it is not likely that the risks on Montserrat will remain both low and stay static. Various scientific predictions (highlighted in the discussions in Chapter 2) have indicated that the volcano will remain active for decades. This author suggests that for Montserrat's future, situations more similar to *SCENARIO B* or *SCENARIO C* are more likely to occur. In those cases, at the model's end date, population reached a level of 6,500 people (see Figure 83) to 7,500 people (see Figure 99). Appendix 4 provides population tables for the four scenarios. Given the situation of continued risk, and the impact that risk has on limiting in-migration, increasing the land fraction occupied, and reducing the rates of housing and business construction, a goal of 10,000 persons may be overly optimistic.

7.3 The Importance of Land Fraction Occupied

The model has indicated that land fraction occupied was a key limiting factor. As indicated in all of the scenarios (with the exception of the high risk scenario), land fraction occupied for zone two and zone three generally rises to a level greater than 90%. The land fraction occupied loop of the model was able to influence the model before the full impacts of the housing and business structure components were able to be realized. While population levels impacted housing, business structures, and jobs to a lesser extent, land fraction occupied provided feedback to the system that resulted in a push and pull of population impacting the entire system.

SCENARIO B illustrated some interesting behavior regarding land fraction occupied (see Figure 78). At 2040 when the risk level for zone 2 passed the critical threshold of 0.6, a large amount of construction had already taken place. When risk is realized by action, some land area is reduced by volcanic actions and in essence the volcano takes what is left and the land fraction occupied spikes to nearly 100% for a short time. This reaction sends population fleeing from zone 2 into zone 3 (see Figure 82). As zone 3 is already nearly occupied to 100% at that point (see Figure 78), the system reacts by sending a small amount of people off the island (see Figure 80) approximately 5 years later, resulting in a decline of total population (see Figure 67).

In *SCENARIO C*, the medium risk with a step, similar behavior takes place (see Figure 94). However, since the step-up in the risk behavior causes the risk level to reach a critical threshold sooner, the spike in the land fraction occupied is lower because the quicker the rate of risk increases, the less time there was for housing and business construction.

7.4 Risk Increase, Population Growth, and Reconstruction

The model has indicated that the population of Montserrat can live with risk and despite the situation of risk being present (and even increasing) population will still increase up to a point. In *SCENARIO A*, with a constant risk of 0.2 (see Figure 59) population reaches the level of 10,000 persons (see Figure 51). In *SCENARIO B* with a four fold increase in risk (See Figure 75), there is still population growth for approximately 35 years (See Figure 67). In experimenting with the model during sensitivity testing, it was found that increases in risk greater than that in *SCENARIO A*, but less than that in *SCENARIO B*, will still allow for population growth.

This information from the model has interesting implications. While it may have seemed reasonable that increased risk would act through the model by driving down both population and construction rates, it was found that risk acts to slow down growth rates, but will not cause a decline in population until risk reaches a level where its actions either reduce the land fraction occupied, reduce construction rates, or push people off the island.

This model's behavior reactions match the real life situation on Montserrat. It is suggested that risk can continue to increase to a certain threshold point while the island's population continues to grow and reconstruction will continue.

7.5 Population Movement

In the medium and high risk scenarios, as risk passes threshold points in zone 2 where it is realized through action, there are spikes in population movement that ripple through the zones in sequential order. Specifically in *SCENARIO D*, movement of population first peaks with movement from zone 1 to zone 2 (see Figure 113), is followed by movement from zone 2 to zone 3 (see Figure 114), and then people are eventually pushed off the island (see Figure 112). Each peak in out-migration is of a greater magnitude, and in *SCENARIO D* that magnitude is reflected in population loss in each zone (see Figure 100) and a total population loss on the island (see Figure 99).

While this spike in population movement is dramatic when depicted graphically, on the ground these spikes would have severe social consequences. In fact, the impacts of the population movements from the eruptions in the late-1990's are still being felt on the island today. When people are moved due to volcanic risk, both family life and economic livelihood are severely impacted. The entire social fabric of the island can quickly start to unravel with such emergency mass movements. If the behavior predicted in the model is accurate in reflecting future population movement between zones under emergency circumstances, the effects on the island's society would be problematic.

7.6 Shock Effects of Group Migration

In Chapter Two, the situation was highlighted regarding a group of Montserratians who temporarily resettled in the United States during the height of the volcanic crisis. The refugees were granted Temporary Protective Status (TPS) to leave the dangerous situation they were living in and seek shelter in the United States. In late-winter 2005, the United States Department of Homeland Security (which manages immigration issues) revoked the Montserratians TPS status claiming that the volcanic eruptions can no longer be considered as a temporary and the volcanic hazard on Montserrat is now a permanent feature of the environment.

This ruling will result in Montserrat refugees in the United States, mostly living in the urban areas of Boston and New York, having to leave migrate back to Montserrat. Such refugees may also have options to relocation to Great Britain (as Montserrat is a British Overseas Territory). While such relocations will be problematic for the refugees for financial and other reasons this situation may have impacts on the model.

For example, if refugees are expelled from a county they evacuated to and sent back to Montserrat, it would result in shock effect of group migration or a pulse in the system. A pulse of hundreds of persons would be added to the island's in-migration numbers. When considering the model's ability to handle this shock, this author suggests that the urban component of the model for zone 3 would be impacted the greatest. As this group of refugees had evacuated from areas that were are now in the exclusion zone, their previous homes and neighborhoods would have been entirely destroyed. This group would in-migrate to zone 3. The pulse of in-migration to zone 3 would result in a corresponding pulse in the population, housing, and business structure state variables. The slope of the line for the land fraction occupied graph in zone 3 would also increase resulting in land fraction occupied reaching its maximum at a faster rate. In the event, a scenario with increased risk is combined with the a pulse for in-migration of refugees, it is suggested that if volcanic risk is realized through action, resulting in a population shift from zone 2 to zone 3, if zone three reaches it land fraction occupied maximum, the model would react by increasing off-migration from the island. Therefore, when policy choices are made to send refugees back to Montserrat through group migration, this new in-migration will be absorbed into the system resulting in a quicker increase in land fraction occupied in zone 3. That circumstance is the likely outcome only under the low risk scenario. However, under any scenario with increasing risk levels, the combined impacts of people evacuating from zone 2 to zone 3 with the shock of the new in-migration will cause the land fraction occupied to reach the maximum resulting in the system responding by sending people off the island.

The Montserrat Urban and Risk Model suggests that the in a situation of increasing risk on the island, sending a group refuges back to the island would quickly result in land fraction occupied increasing to a level where the model responds by sending people of the island. It is suggested that if there is a situation of increasing risk, it would be of limited utility to try to send refuges back to Montserrat, as shortly after they arrive they would either have to leave again, of others would have to leave in their place due to land constraints Despite, social and political factors driving decisions to revoke Montserratian's TPS status in the United States, it would likely be the case that the island would have difficulty in absorbing a shock of new population and the population sent back to Montserrat may again be forced to become refugees. However, this time the refugees would be driven off the island due to land constraints combined with the impacts of the volcanic hazard.

7.7 Comments on Risk Perception

The impacts of risk perception are most dramatically observed in *SCENARIO C*. Risk perception was designed into the system dynamics model as an information delay function. Information delay functions are graphically represented by a smoothing effect. When the increase takes place in risk, risk perception follows, but on a delayed basis (See Figure 91). This behavior results in an observable smoothing effect for the risk perception line in the graph. However, the smooth can only have the effect of delaying the realization of the risk, not lowering it. Similar to how risk takes action when it rises above certain thresholds, as the risk perception level rises to critical threshold levels it is realized by the action of a decrease in the island's in-migration rate (see Figure 95).

This behavior of the model would correspond to how risk perception is acted on in crisis situations. While the risk would be first realized on by people on Montserrat, though various channels the risk would be communicated (and perhaps amplified) to people overseas. In Chapter Three, the section on risk communication and the social amplification of risk comments on those risk-related behaviors. After the information is communicated by various means and then processed by the individual (taking time, thus the delay) the individual would take action. In this case, the action would be deciding to stay in place and not return to Montserrat for the time-being. Such delay and uncertainty, leading to a lack of action would cause Montserrat's in-migration rate to be lowered.

7.8 Overall Pressure To Move Closer the Volcano

While perhaps beyond the parameters established in this model, a trend is clearly starting that will definitely impact Montserrat in the future. That trend involved the land fraction occupied reaching high level in the zones furthest from the volcano. A good example is illustrated in *SCENARIO B* (see Figure 78). In the safest zone, zone 3, the land fraction occupied increases to nearly 100%, while in zone 1 and 2 the actions of risk result in an increase of land fraction occupied, and then a decrease as a combination as housing (see Figure 69) and business structures (see Figure 72) are leveled through the demolition rate as influenced by risk.

However, once these risk activities end, and the volcano quiets down, at some point in the future, the zone 3 will be very crowded, while zone one and two will have land available for development. Despite the ever present risks of moving closer to the volcano, it may be that case that the everyday impacts of overcrowding may overwhelm the more abstract concepts of volcanic risks for those persons making future decisions concerning where to live on Montserrat. People may start to migrate to areas closer to the volcano to relieve the symptoms of overcrowding. However, these actions would be dangerous, as the volcano is likely to remain active for hundreds of years. The difficulties of comprehending the long-term risks of the volcano (measured in geological time) versus more short-term day-to-day difficulties faced by coping with effects of past-disasters may result in poor choices being made. It may be the case that one can live for a lifetime next to a volcano, or in a coastal zone that is under threat from tsunamis, and not be impacted. However, even if risks are not realized during a lifetime, it does not indicate that risks are non-existent (especially for longer term geological phenomenon). If one happens to be the person in the wrong place at the wrong time, when their lifetime intersects with actions of long-term geologic forces the results can be deadly. It is interesting to note that on Montserrat, prior to 1995, the volcano was not known to have erupted since records were kept by Europeans who first settled the island in 1632. While in hindsight, one can claim that it did not necessarily make the best sense for a majority of Montserrat's human settlements to be located in close proximity to the volcano, it could be argued that the area was seemingly safe, as shown by nearly 400 years of history. However 400 years is only a very short-time in the life of a volcano.

CHAPTER 8

SUMMARY, LIMITATIONS, AND CONCLUSIONS

8.1 Summary

This study involves investigating the disaster recovery on Montserrat, British West Indies. In the late-1990s, a series of catastrophic volcanic eruptions destroyed two-thirds of the island and caused over 60% of the population to evacuate. By 1999, recovery from the disaster had started with the reconstruction of new towns at the northernmost end of the island, deemed as the northern safe zone. Due to the volcanic hazard, the southern two-thirds of the island remain as an exclusion zone to this day. A redevelopment goal was established of reconstructing the island to the point that it can support 10,000 persons. The primary research problem is: "Is the post-disaster redevelopment goal for Montserrat of reaching 10,000 persons feasible given a situation of development constraints and continued risk." The method of system dynamics modeling (based after the work of Forrester) is applied in this study. A computer-based model was developed based on Forrester's urban model, and the model was adapted to the case on Montserrat. Specifically, spatial elements were added to the model based on the geography of three areas of the safe zone, and a risk component was added simulate risk from the volcano. The Montserrat Urban & Risk Model was simulated over four scenarios with variations in risk conditions ranging from low to high. Key state variables of population, housing, business structures, and land faction occupied, and risk were simulated over a 50 year time horizon. It was determined that unless there is a condition of low risk, it is not feasible for Montserrat to reach a population of 10,000 people in the next 50 years. Land fraction occupied was found to be a key limiting factor and that element of the model would be a policy lever in the system. This author suggests a goal of 6,500 to 7,500 persons is an appropriate redevelopment target.

8.2 Model Limitations

In the Montserrat Urban and Risk Model, an urban model was adapted to the case of Montserrat and geographic and risk components were added to the model. The state variables in the model were population, housing, business structures, actual risk, and perceived risk.

While economic considerations were factored into the model as a proxy of business structures and jobs, this model does not take into account economic factors such as the British aid needed to support the functioning of society. As Montserrat is still recovering from the disaster, its economy has not fully recovered and overseas aid is needed to supply the island with basic needs, and to support the population with grant and aid programs and social welfare while they can rebuild their livelihoods.

The model assumes that British aid remains at a level that is adequate to support the current population and that aid will remain at a level sufficient to support the growth and redevelopment of the island.

In addition, sustainability considerations may limit the level of redevelopment on the island. In terms of resources, in the Montserrat Urban and Risk Model applied in this study, considers land fraction occupied. Land fraction occupied allows for the land resource to be quantified, however the model assumes that other natural resources are present at a level that is adequate to support the population.

As Montserrat is both geographically isolated and resource constrained, sustainability considerations are an important part of considering to best to redevelop the island. While land is the main resource constraint, other resources such as the portion of arable land, agricultural output, potable water, energy resources, fisheries, forestry, etc. are all needed to support the population. While this model is limited to the extent that it does not disaggregate resources and model sustainability elements of the island other than land, sustainability considerations are an area for expansion of this research.

8.3 Recommendations: Policy Implications

The model's output has indicated that the variable of land fraction occupied was a key limiting factor. When an increasing risk is realized by the action of reducing the land available for development, the land fraction occupied is driven up. Given that the land area was already built up to a certain level, increased risk results in pushing the land fraction occupied to nearly 100% pushing people from one zone to another or pushing people off the island entirely. The effects of land fraction occupied were most clearly noticed in zone 2 and zone 3. If a redevelopment goal is to reach a population of 10,000 persons, it will be necessary to keep the existing population from leaving while attracting new population through in-migration. However, as it likely that risk will continue to increase for the foreseeable future, it may become necessary for persons to leave zones of higher risk and move to zones of lower risk. The model has indicated that the chances to exercise that option will become extremely limited. Under low to moderate risk conditions, during the next 30 years, the model indicated a construction boom will take place, where houses and business structures will fill both zones 2 and 3 to the point where the land fraction occupied reaches a level greater than 90%.

While it may seem counterintuitive, this author suggests enacting a policy limiting development in zone 3, the northernmost zone. While this zone faces the least risk and for that reason is most desirable for development, it also will reach its capacity for absorbing new development in the near-term. A policy strategy of holding land open in zone 3 for potential future development would serve as a mitigation measure for future population loss due to increased risk. Such a policy could be enacted by strategies such as designating areas for land uses such as passive recreation, open space reserves, or sporting activities. Such uses could keep the land available for future development under emergency situations.

For example, when the level of risk increases past critical thresholds people would move from zone 2 to zone 3. However, as the model indicates, such movement of population from areas of higher risk to areas of lower risk results in the land fraction occupied in zone three reacting levels greater than 90%. In that situation any further influx of people will result in a people being pushed off the island as there is not any land area remaining to support these people. This situation takes place in the high risk scenario when due the risk, people migrate north, the land fraction occupied reaches the maximum, and people are pushed off the island as the land available for development is at a minimum.

Alternatively with the policy recommendation being suggested, in the event risk pushes people from zone 2 into zone 3, the land set aside for passive uses can be quickly converted to land suitable for the development of homes and business structures. By exploiting this excess capacity for development, instead of being forced off the island the land capacity in reserve could be used to keep those people on the island.

Under the best case scenario, land set aside for passive recreation, open space reserves, or sporting fields would increase the island's quality of life, while artificially lowering the land fraction occupied in zone 3. Under the worst case scenario, volcanic risk would push persons into areas with these lands set aside, and the passive land uses would need to be converted to human settlements. However, that segment of the population would still be able to remain on the island without leaving themselves or pushing others off the island. Therefore, the policy would act to reduce population loss so the island could reach its stated development goal of 10,000 persons quicker.

8.4 Recommendations: Future Research

Based on the initial work completed in this study, four areas for future research are recommended. First regarding risk, in the model applied to this study risk was taken as an aggregate measure. An area of expansion of the model would be to disaggregate risk into various types. For example, volcano risk, hurricane risk, landslide risk, and tsunami risk could all be incorporated into the model, each having different impacts on key resources. Along the same lines, a second area of model disaggregation would be population. The population state variable could be disaggregated into separate groups and systems of group dynamics could be added to get a more accurate reflection of population dynamics on the island. For example, people native to Montserrat, a guest worker class, a merchant class, British civil servants, and expatriates could all be modeled as groups with separate attributes concerning risk, differing housing choices, and differing economic opportunities. A third area of expansion would be enhancing the geographic components of the model. While the three zone model was used in this study, using similar concepts many different zones could be developed. The island could be divided into a spatial grid system and each zone could be fine tuned with specific spatial attributes to accurately reflect conditions that impact risk realization, construction rate, land fraction occupied, etc. A powerful tool that would be worthwhile investigating is the integration of geographic information systems with system dynamic modeling. A fourth area of expansion would be to more closely link spatial-temporal models of disaster recovery to theories regarding the disaster life cycle and the four phases of disaster recovery. In cases such as Montserrat, the premises of the linear model of disaster recovery do not hold up well. Spatial-temporal models could perhaps be very useful in providing information to better conceptualize disaster recovery, the least understood element of the disaster cycle.

8.5 Personal Insights as Related to Model Output

During the course of this research, the author has gained personal insights into the situation of Montserrat's disaster recovery. Two main insights relate to the model's output and interpretation. Those insights are related to the strong ethic of resiliency and risk perception.

During the volcanic crisis persons on Montserrat have shown a high degree of resiliency and as they have a great ability to cope with the crisis. Even during the worst episodes of the volcanic eruption in 1996 and 1997, almost 3,000 persons remained on the island. While some of those persons did not have the ability to leave, others had made the choice to stay in place despite the disaster. For a variety of reasons, ranging from sense of place, to financial reasons, to fatalism, many of the persons who stayed on the island during the crisis likely felt that even though the crisis was one of the worst disasters of the late-1990s, they still would fare better on their island than they would by evacuating. The citizenry of Montserrat should be commended for the degree to which they have exhibited a high degree of resiliency during the crisis. This insight suggests that even though under the worst case risk scenario, the population of the island begins to decline, it is very unlikely that population will ever reach zero or that any program to totally evacuate the island would proceed smoothly as there will always be a portion of the population who will show extreme resiliency, and refuse to leave, regardless of the circumstances they find themselves in.

Another insight relates to risk perception. In the model, risk perception was incorporated as first order information delay function to influence to amount of in-migration. This author suggests that risk perception has a much greater influence to those persons off Montserrat, than those persons on Montserrat. As mentioned above, persons on the island develop a high degree of resiliency which is needed for day-to-day survival. What would be perceived by many persons person not familiar with the volcanic eruptions as an emergency requiring extreme action would be perceived by persons dealing with the crisis on a day-to-day basis as nothing out of the ordinary. For example, on occasion media reports show a volcanic event through imagery such as an ash cloud reaching tens of thousands of feet in altitude. As these ash clouds appear to dwarf the small island, for one seeing aerial imagery of these eruptions it is hard to imagine living at ground zero of these eruptions. While it is beyond the scope of this study, it is likely such images of the disaster and sensationalistic disaster reporting combine to give people who receive these reports a perception that the risk is very high. However, for those persons on Montserrat coping with crisis, it is likely that they have become used to ash fallout, and that if a volcanic events result in ash only but no further destruction of land and resources outside of the exclusion zone, the event will not be viewed as a high risk event, but more as an inconvenience.

This author suggests that during further study of the Montserrat crisis, the differences in risk perception between those persons living on the island and those persons living off the island would be an interesting area of study. From the limited amount of insight into the risk perception gained from this study, it is suggested that risk perception will strengthen the determination of those people who are already on the island to stay put and provide a rationale for those persons who are off the island to remain off the island.

8.6 Conclusions

While this study was based on conditions related to Montserrat and the risks presented by Montserrat's volcano, this author foresees this modeling methodology being made applicable to other situation of volcanic hazards and even other hazards. The strengths of Forrester's original urban model, combined with risk and spatial components allow for a powerful technique that can be used for experiments. Large scale disasters are very difficult to grasp, as the December 2004 tsunami has illustrated the complexities of dealing with large scale events. System dynamics allows for modeling the bigger picture in order to take a step back and consider the wide ranging consequences of disaster events. When responding to a crisis, one does not have the ability to experiment with considering the outcomes of various actions. Well meaning actions often result in unintended consequences. To limit unintended consequences, this author suggests the area of disaster recovery offers many opportunities for the application of spatial-temporal modeling to help to better assist those persons in need.

APPENDICES

APPENDIX 1

DESCRIPTION OF MODEL COMPONENTS

Appendix 1 provides a detailed description of the model components including flowcharts, assumptions, equations, and variables assigned in eleven parts as follows:

- **Figure A1** depicts the In-Migration Component of the Model and **Table A1** provides a detailed description of the variables.

- **Figure A2** depicts the Population Component of the Model for Zone 1 and **Table A2** provides a detailed description of the variables.

- **Figure A3** depicts the Housing Component of the Model for Zone 1 and **Table A3** provides a detailed description of the variables

- **Figure A4** depicts the Population Component of the Model for Zone 2 and **Table A4** provides a detailed description of the variables.

- **Figure A5** depicts the Housing Component of the Model for Zone 2 and **Table A5** provides a detailed description of the variables.

- **Figure A6** depicts the Business Structure Component of the Model for Zone 2 and **Table A6** provides a detailed description of the variables.

- **Table A7** provides a detailed description of Population, Housing, and Business Structure Components for Zone 3 which differ from the diagram and table for Zone 2.

- **Figure A8** depicts the Actual and Perceived Risk for the Entire Model and **Table A8** provides a detailed description of the variables.

- **Figure A9** depicts Risk as Realized by Zone for Zone 1 and **Table A9** provides a detailed description of the variables.

- **Table A10** provides a detailed description of the variables for Risk as Realized in Zone 2 as they differ from the Diagram and Table for Zone 1.

- **Table A11** provides a detailed description of the variables for Risk as Realized in Zone 3 as they differ from the Diagram and Table for Zone 1.

- All of the Models in this study were developed using the computer modeling software **Powersim Studio Research Academic 2005 (Version 6.00.3372.6)**

APPENDIX 1

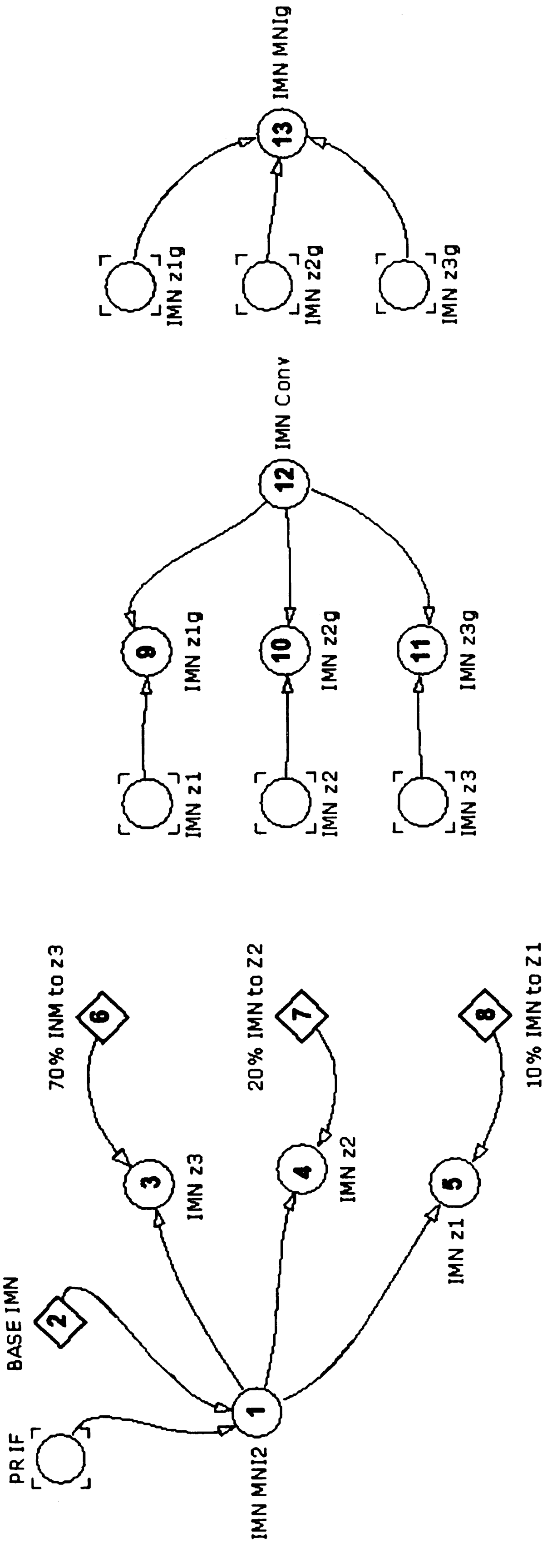


Figure A1. In-Migration Component of Montserrat Urban and Risk Model

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A1. Description of Model Components in Figure A1

# in Figure	**1**
Variable Abbreviation	**IMN MNI2**
Variable Name	In-Migration Normal for Montserrat
Variable Type	Auxiliary
Variable Definition	= 'PR IF'*'BASE IMN'
Base Value	Calculated
Units	1/year
Additional Comments	
# in Figure	**2**
Variable Abbreviation	**BASE IMN**
Variable Name	Base In-Migration Normal
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.1125
Units	1/year
Additional Comments	Set as equivalent to 1,125 persons per year, estimated from average immigration data 1995-2005, see chapter 2 for population data sources

APPENDIX 1 (continued)

# in Figure	**3**
Variable Abbreviation	**IMN z3**
Variable Name	In-Migration Normal for zone 3
Variable Type	Auxiliary
Variable Definition	= 'IMN MNI2'*'70% INM to z3'
Base Value	Calculated
Units	1/year
Additional Comments	

# in Figure	**4**
Variable Abbreviation	**IMN z2**
Variable Name	In-Migration Normal for zone 2
Variable Type	Auxiliary
Variable Definition	= 'IMN MNI2'*'20% IMN to Z2'
Base Value	Calculated
Units	1/year
Additional Comments	

# in Figure	**5**
Variable Abbreviation	**IMN z1**
Variable Name	In-Migration Normal for zone 1
Variable Type	Auxiliary
Variable Definition	= 'IMN MNI2'*'10% IMN to Z1'
Base Value	calculated
Units	1/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**6**
Variable Abbreviation	**70% INN to z3**
Variable Name	70 % of in-migration to zone 3
Variable Type	Constant
Variable Definition	= 0.7
Base Value	n/a
Units	Dimensionless
Additional Comments	See Figure 44

# in Figure	**7**
Variable Abbreviation	**20% INN to z2**
Variable Name	20 % of in-migration to zone 2
Variable Type	Constant
Variable Definition	= 0.2
Base Value	n/a
Units	Dimensionless
Additional Comments	See Figure 44

# in Figure	**8**
Variable Abbreviation	**10% INN to z3**
Variable Name	10 % of in-migration to zone 1
Variable Type	Constant
Variable Definition	= 0.1
Base Value	n/a
Units	dimensionless
Additional Comments	See Figure 44

APPENDIX 1 (continued)

# in Figure	**9**
Variable Abbreviation	**IMN z1g**
Variable Name	In-Migration Normal for Z1 (for Graph)
Variable Type	Auxillary
Variable Definition	= 'IMN z1'*'IMN Conv'
Base Value	n/a
Units	ppl
Additional Comments	Used for Conversion to People for Graphs
# in Figure	**10**
Variable Abbreviation	**IMN z2g**
Variable Name	In-Migration Normal for Z2 (for Graph)
Variable Type	Auxillary
Variable Definition	= 'IMN Conv'*'IMN z2'
Base Value	n/a
Units	ppl
Additional Comments	Used for Conversion to People for Graphs
# in Figure	**11**
Variable Abbreviation	**IMN z3g**
Variable Name	In-Migration Normal for zone 3 (for Graph)
Variable Type	Auxillary
Variable Definition	= 'IMN Conv'*'IMN z3'
Base Value	n/a
Units	ppl
Additional Comments	Used for Conversion to People for Graphs

APPENDIX 1 (continued)

# in Figure	**12**
Variable Abbreviation	**IMN CONV**
Variable Name	In-Migration Normal Converter
Variable Type	Auxillary
Variable Definition	= 1000
Base Value	n/a
Units	ppl * yr
Additional Comments	Used for Conversion to People for Graphs
# in Figure	**13**
Variable Abbreviation	**IMN MNIg**
Variable Name	Total In-Migration to Montserrat
Variable Type	Auxillary
Variable Definition	= 'IMN z1g'+'IMN z2g'+'IMN z3g'
Base Value	calculated
Units	ppl
Additional Comments	Used for Generating Output

APPENDIX 1 (Continued)

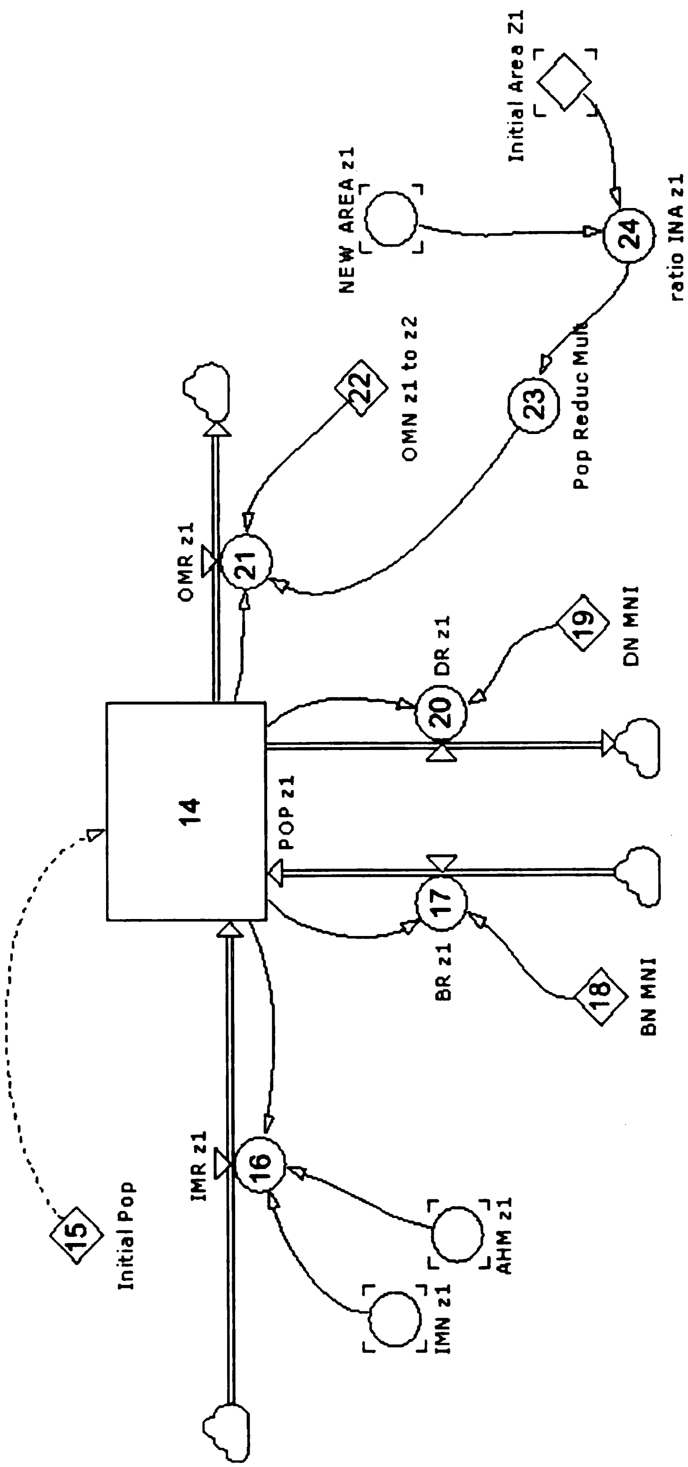


Figure A2. Population Component for Zone 1

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A2. Description of Model Components in Figure A2

# in Figure	**14**
Variable Abbreviation	**POP Z1**
Variable Name	Population for Zone 1
Variable Type	State Variable
Variable Definition	= 'Initial Pop'
Base Value	1,173
Units	ppl
Additional Comments	See Chapter section 5.3.2 for discussion of population sources
# in Figure	**15**
Variable Abbreviation	**Initial Pop**
Variable Name	Initial Population for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 1,173
Units	ppl
Additional Comments	See Chapter section 5.3.2 for discussion of population sources

APPENDIX 1 (continued)

# in Figure	**16**
Variable Abbreviation	**IMR z1**
Variable Name	In-Migration Rate for Zone 1
Variable Type	Rate
Variable Definition	= ('POP z1'*'IMN z1')*'AHM z1'
Base Value	Calculated
Units	ppl/year
Additional Comments	
# in Figure	**17**
Variable Abbreviation	**BR z1**
Variable Name	Birth Rate for Zone 1
Variable Type	Rate
Variable Definition	= 'POP z1'*'BN MNI'
Base Value	Calculated
Units	ppl/year
Additional Comments	
# in Figure	**18**
Variable Abbreviation	**BN MNI**
Variable Name	Birth Rate Normal for Montserrat
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.018
Units	1/year
Additional Comments	Equivalent to birth rate of 18 per 1000, source CIA Factbook year 2000 data

APPENDIX 1 (continued)

# in Figure	**19**
Variable Abbreviation	**DN MNI**
Variable Name	Death Rate Normal for Montserrat
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.009
Units	1/year
Additional Comments	Equivalent to death rate of 9 per 1000, source CIA Factbook year 2000 data

# in Figure	**20**
Variable Abbreviation	**DR z1**
Variable Name	Death Rate for Zone 1
Variable Type	Rate
Variable Definition	= 'POP z1'*'DN MNI'
Base Value	calculated
Units	ppl/year
Additional Comments	

# in Figure	**21**
Variable Abbreviation	**OMR z1**
Variable Name	Out-migration rate for Zone 1
Variable Type	Rate
Variable Definition	= ('POP z1'*'OMN z1 to z2')*'Pop Reduc Mult'
Base Value	Calculated
Units	Dimensionless
Additional Comments	ppl/year

APPENDIX 1 (continued)

# in Figure	**22**
Variable Abbreviation	**OMN z1 to z2**
Variable Name	Out-Migration Normal from Zone 1 to Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.30
Units	1/yr
Additional Comments	

# in Figure	**23**
Variable Abbreviation	**Pop Reduc Mult**
Variable Name	Population Reduction Multiplier
Variable Type	Auxiliary – Table Function
Variable Definition	= GRAPH('ratio INA z1' ,0,.30176,{1,1,1,1,1,1,3,3,3 //Min:0;Max:4//})
Base Value	calculated
Units	n/a
Additional Comments	Impact of Risk on Population

# in Figure	**24**
Variable Abbreviation	**IMN z3g**
Variable Name	Ratio of Initial Area to New Area
Variable Type	Auxiliary - Ratio
Variable Definition	= 'Initial Area Z1'/'NEW AREA z1'
Base Value	calculated
Units	dimensionless
Additional Comments	Impact of Risk on Population

APPENDIX 1 (Continued)

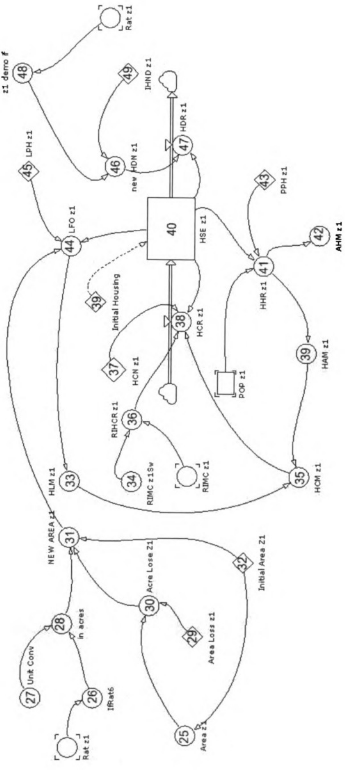


Figure A3. Housing Component for Zone 1

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A3. Description of Model Components in Figure A3

# in Figure	**25**
Variable Abbreviation	**Area z1**
Variable Name	Areas for Zone1
Variable Type	Auxiliary
Variable Definition	= 'Initial Area Z1'
Base Value	778
Units	acres
Additional Comments	See Figure 42 for sources
# in Figure	**26**
Variable Abbreviation	**IfRat6**
Variable Name	Risk Area Threshold for Zone 1
Variable Type	Auxiliary
Variable Definition	= IF('Rat z1'> .6<<risk_unit>>,1<<risk_unit>>, 0 <<risk_unit>> , 0<<risk_unit>>)
Base Value	Calculated
Units	risk unit
Additional Comments	Risk as realized by action threshold function

APPENDIX 1 (continued)

# in Figure	**27**
Variable Abbreviation	**Unit Conv**
Variable Name	Risk and Area Unit Converter for Zone 1
Variable Type	Auxiliary
Variable Definition	1
Base Value	n/a
Units	Acre / risk unit
Additional Comments	Unit converter

# in Figure	**28**
Variable Abbreviation	**in acres**
Variable Name	Acre conversion Function for Zone 1
Variable Type	Auxiliary
Variable Definition	= IfRat6*'Unit Conv'
Base Value	Calculated
Units	Acre
Additional Comments	converter

# in Figure	**29**
Variable Abbreviation	**Area Loss Z1**
Variable Name	Areas Loss for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.45
Units	1/acre
Additional Comments	Land area reduced when risk realized by action

APPENDIX 1 (continued)

# in Figure	**30**
Variable Abbreviation	**Acre Loss Z1**
Variable Name	Acres Lost in Zone 1
Variable Type	Auxiliary
Variable Definition	= 'Area z1'*'Area Loss z1'
Base Value	= calculated
Units	Dimensionless
Additional Comments	
# in Figure	**31**
Variable Abbreviation	**NEW AREA Z1**
Variable Name	New Area for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'Initial Area Z1'-('in acres'*'Acre Lose Z1')
Base Value	calculated
Units	acres
Additional Comments	
# in Figure	**32**
Variable Abbreviation	**Initial Area Z1**
Variable Name	Initial Areas for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	778
Units	acres
Additional Comments	See Figure 42 for sources

APPENDIX 1 (continued)

# in Figure	**33**
Variable Abbreviation	**HLM z1**
Variable Name	Housing Land Multiplier for Zone 1
Variable Type	Auxiliary – Table Function
Variable Definition	GRAPH('LFO z1',0,.1,{.4,.7,1,1.25,1.45,1.5,1.5, 1.4,1,.5,0 /Min:0;Max:2//})
Base Value	= calculated
Units	n/a
Additional Comments	From urban model
# in Figure	**34**
Variable Abbreviation	**RIMC z1Sw**
Variable Name	Risk and In-Migration Switch for Zone 1
Variable Type	Auxiliary – Switch
Variable Definition	= 1
Base Value	n/a
Units	n/a
Additional Comments	switch
# in Figure	**35**
Variable Abbreviation	**HCM z1**
Variable Name	Housing Construction Multiplier for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'HAM z1'*'HLM z1'
Base Value	calculated
Units	dimensionless
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**36**
Variable Abbreviation	**RIHCRz1**
Variable Name	Risk and Housing Construction Zone 1
Variable Type	Auxiliary
Variable Definition	= 'RIMC z1'*'RIMC z1Sw'
Base Value	Calculated
Units	Dimensionless
Additional Comments	
# in Figure	**37**
Variable Abbreviation	**HCN Z1**
Variable Name	Housing Construction Normal for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.10
Units	Set for Rate of 100 constructed per 1000
Additional Comments	See Chapter 5
# in Figure	**38**
Variable Abbreviation	**HCR z1**
Variable Name	Housing Construction Rate for Zone 1
Variable Type	Rate
Variable Definition	= 'HSE z1'*'HCN z1'*'HCM z1'*'RIHCR z1'
Base Value	Calculated
Units	hse/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**39**
Variable Abbreviation	**Initial Housing**
Variable Name	Initial Number of Houses in Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 293
Units	hse
Additional Comments	See housing discussion in Chapter 5 / Physical Dev. Plan

# in Figure	**40**
Variable Abbreviation	**HSE Z1**
Variable Name	Houses in Zone 1
Variable Type	State Variable
Variable Definition	= 'Initial Housing'
Base Value	= 293
Units	hse
Additional Comments	

# in Figure	**41**
Variable Abbreviation	**HHR z1**
Variable Name	Housing to Household Ratio
Variable Type	Auxiliary - Ratio
Variable Definition	= 'POP z1'/('HSE z1'*'PPH z1')
Base Value	Calculated
Units	dimensionless
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**42**
Variable Abbreviation	**AHM z1**
Variable Name	Attractiveness of Housing Multiplier for Zone 1
Variable Type	Auxiliary – Table Function
Variable Definition	= GRAPH('HHR z1',0,.2, {1.4,1.4,1.35,1.3,1.15,1,.80,.650, .50,.450,.4 //Min:0;Max:2//})
Base Value	= calculated
Units	n/a
Additional Comments	

# in Figure	**43**
Variable Abbreviation	**PPH z1**
Variable Name	People per Household for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 4
Units	People per house
Additional Comments	Source: See Chapter 5 and Physical development plan

# in Figure	**44**
Variable Abbreviation	**LFO z1**
Variable Name	Land Fraction Occupied for Zone 1
Variable Type	Auxiliary
Variable Definition	= ('HSE z1'*'LPH z1')/'NEW AREA z1'
Base Value	Calculated
Units	dimensionless
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**45**
Variable Abbreviation	**LPH z1**
Variable Name	Land Per House for Zone 1
Variable Type	Constant
Variable Definition	n/a)
Base Value	= 0.17
Units	acre/hse
Additional Comments	Equivalent to six houses per acre / see Chapter 5
# in Figure	**46**
Variable Abbreviation	**NEW HDN z1**
Variable Name	New Housing Demolition Normal for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'IHND z1'*'z1 demo if'
Base Value	= calculated
Units	1/year
Additional Comments	
# in Figure	**47**
Variable Abbreviation	**HDR z1**
Variable Name	Housing Demolition Rate for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'HSE z1'*'new HDN z1'
Base Value	Calculated
Units	hse/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**48**
Variable Abbreviation	**Z1 demo if**
Variable Name	Housing Demolition by Risk in Zone 1
Variable Type	Auxiliary
Variable Definition	= IF('Rat z1'>.6<<risk_unit>>,4,1)
Base Value	= calculated
Units	n/a
Additional Comments	Risk by Action Thresholds - demolition
# in Figure	**49**
Variable Abbreviation	**IHND z1**
Variable Name	Initial Housing Demolition Normal for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.005
Units	1/year
Additional Comments	Equivalent to 5 per 1,000 / based on chapter five scenario development

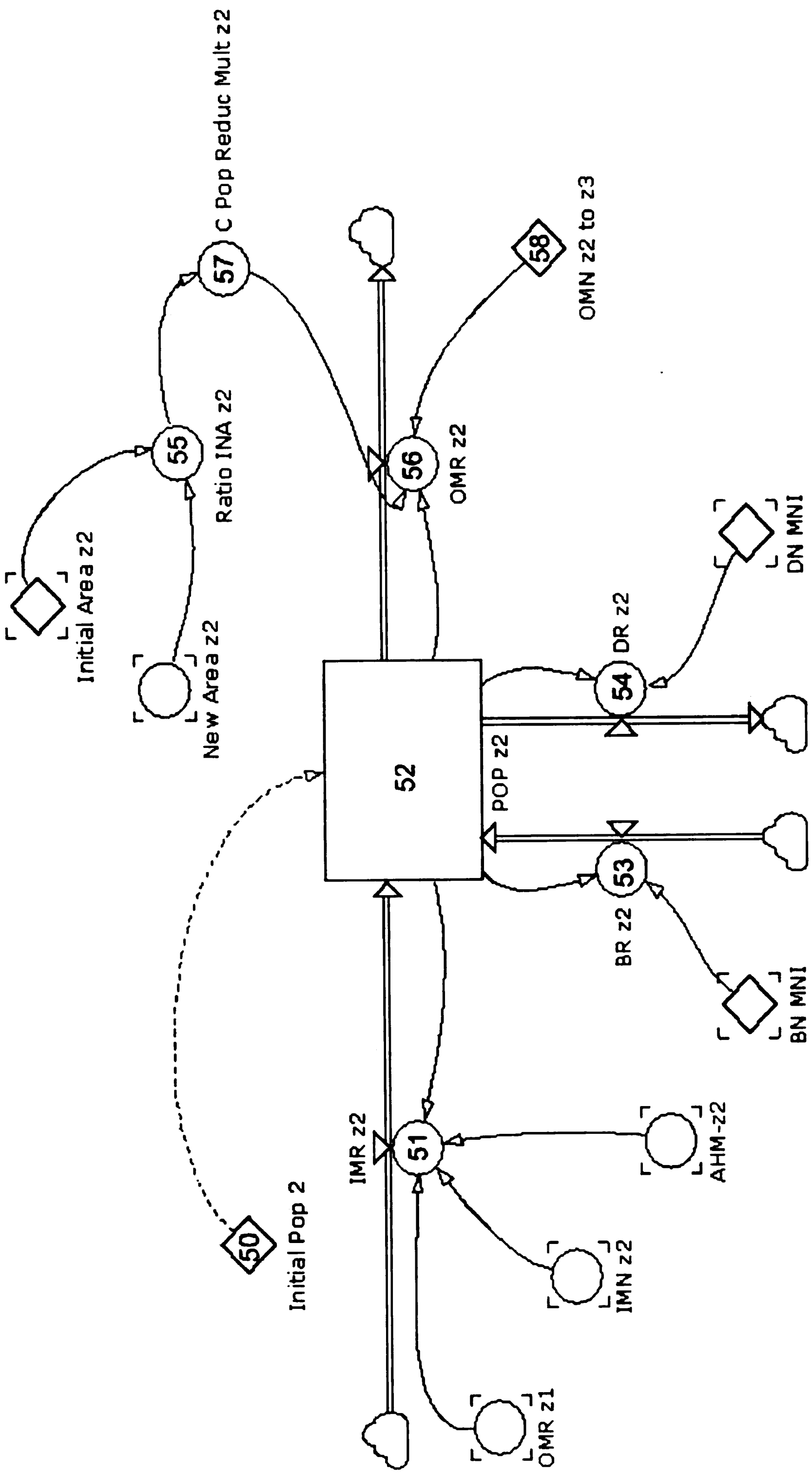


Figure A4. Population Component for Zone 2

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A4. Description of Model Components in Figure A4

# in Figure	**50**
Variable Abbreviation	**Initial Pop 2**
Variable Name	Initial Population for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 1,407
Units	ppl
Additional Comments	See Chap. 5 section 5.3.2 for discussion of population sources
# in Figure	**51**
Variable Abbreviation	**IMR z2**
Variable Name	In-Migration Rate for Zone 2
Variable Type	Rate
Variable Definition	= ('POP z2'*'IMN z2'*'AHM-z2')+'OMR z1'
Base Value	Calculated
Units	ppl/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**52**
Variable Abbreviation	**POP z2**
Variable Name	Population for Zone 2
Variable Type	State
Variable Definition	= 'Initial Pop 2'
Base Value	= 1,407
Units	ppl
Additional Comments	See Chap. 5 section 5.3.2 for discussion of population sources
# in Figure	**53**
Variable Abbreviation	**BR z2**
Variable Name	Birth Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'BN MNI'*'POP z2'
Base Value	Calculated
Units	ppl/yr
Additional Comments	
# in Figure	**54**
Variable Abbreviation	**DR z2**
Variable Name	Death Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'POP z2'*'DN MNI'
Base Value	calculated
Units	ppl/yr
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**55**
Variable Abbreviation	**Ratio INA z2**
Variable Name	Ratio Initial to New Area for zone 2
Variable Type	Auxiliary - ratio
Variable Definition	= 'Initial Area z2'/'New Area z2'
Base Value	calculated
Units	Dimensionless
Additional Comments	Related to risk function
# in Figure	**56**
Variable Abbreviation	**OMR z2**
Variable Name	Out-Migration Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'Initial Area z2'/'New Area z2'
Base Value	Calculated
Units	Dimensionless
Additional Comments	
# in Figure	**57**
Variable Abbreviation	**C Pop Reduc Mult z2**
Variable Name	Population Reduction Multiplier for Zone 2
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('Ratio INA z2',0,.133,{1,1,1,1,1,1,1,1,1,1,3,3,3,3,3 //Min:0;Max:4//})
Base Value	Calculated
Units	n/a
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**58**
Variable Abbreviation	**OMN z2 to z3**
Variable Name	Out-Migration Normal from Zone 2 to Zone 3
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.028
Units	1/year
Additional Comments	Geographic Component, Normal Movement of 28 per 1000

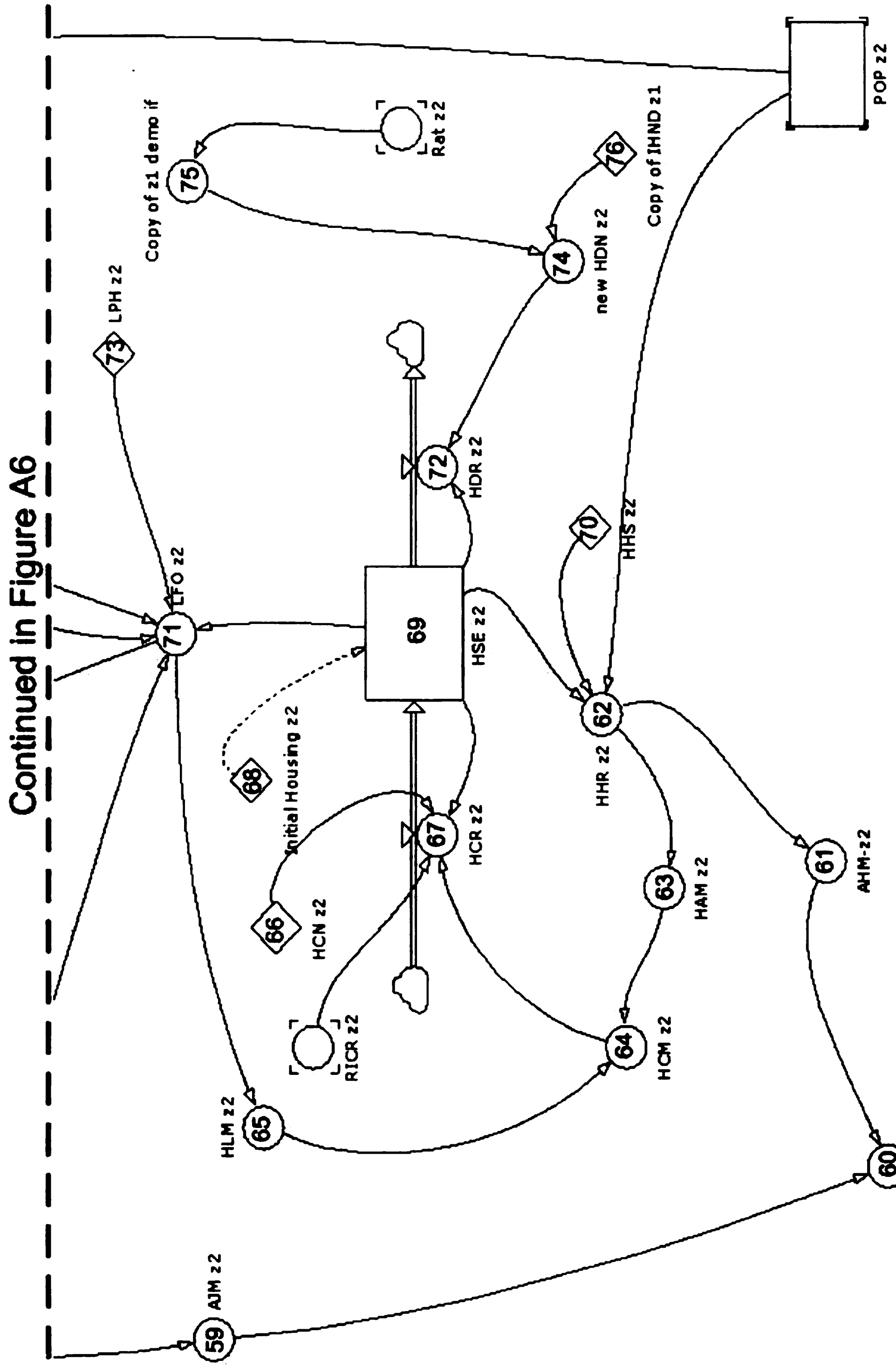


Figure A5. Housing Component for Zone 2

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A5. Description of Model Components in Figure A5

# in Figure	**59**
Variable Abbreviation	**AJM z2**
Variable Name	Attractiveness of Jobs Multipliers for Zone 2
Variable Type	Auxiliary – Table Function
Variable Definition	= GRAPH('LFJR z2',0,.2,{2,1.95,1.80,1.6,1.35,1,.50,.3,.20, .150,.1//Min:0;Max:2//})
Base Value	Calculated
Units	n/a
Additional Comments	From urban model
# in Figure	**60**
Variable Abbreviation	**AM z2**
Variable Name	Attractiveness Multipliers for Zone 2
Variable Type	Auxiliary
Variable Definition	= 'AJM z2'*'AHM-z2'
Base Value	Calculated
Units	dimensionless
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**61**
Variable Abbreviation	**AHM z2**
Variable Name	Attractiveness of Housing Multiplier for Zone 2
Variable Type	Auxiliary – table function
Variable Definition	GRAPH('HHR z2',0,.2,{1.4,1.4,1.35,1.3,1.15,1,.80,.650,.50, .450,.4//Min:0;Max:2//})
Base Value	Calculated
Units	n/a
Additional Comments	From urban model

# in Figure	**62**
Variable Abbreviation	**HHR z2**
Variable Name	Houses to Households ratio
Variable Type	Auxiliary – ratio
Variable Definition	= 'POP z2'/('HSE z2'*'HHS z2')
Base Value	Calculated
Units	dimensionless
Additional Comments	

# in Figure	**63**
Variable Abbreviation	**HAM z2**
Variable Name	Housing Attractiveness Multiplier
Variable Type	Auxiliary – table function
Variable Definition	=GRAPH('HHR z2',0,.2,{.1,.2,0.35,0.5,0.7,1,1.35,1.6, 1.80,1.95,2//Min:0;Max:2//}
Base Value	Calculated
Units	n/a
Additional Comments	From urban model

APPENDIX 1 (continued)

# in Figure	**64**
Variable Abbreviation	**HCM z2**
Variable Name	Housing Construction Multiplier for zone 2
Variable Type	Auxiliary
Variable Definition	= 'HAM z2'*'HLM z2'
Base Value	Calculated
Units	Dimensionless
Additional Comments	

# in Figure	**65**
Variable Abbreviation	**HLM z2**
Variable Name	Housing Land Multiplier for zone 2
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('LFO z2',0,.1,{.4,.7,1,1.25,1.45,1.5,1.5, 1.4,1,.5,0//Min:0;Max:2//})
Base Value	Calculated
Units	n/a
Additional Comments	From urban model

# in Figure	**66**
Variable Abbreviation	**HCN z2**
Variable Name	Housing Construction Normal for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	=0.03
Units	1/year
Additional Comments	Set for 30 per 1000, see discussion in Chapter 5

APPENDIX 1 (continued)

# in Figure	**67**
Variable Abbreviation	**HCR z2**
Variable Name	Housing Construction Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'HSE z2'*'HCN z2'*'HCM z2'*'RICR z2'
Base Value	calculated
Units	Hse/year
Additional Comments	

# in Figure	**68**
Variable Abbreviation	**Initial Housing z2**
Variable Name	Initial Housing z2 for zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 352
Units	hse
Additional Comments	See discussion in Chap 5 and Physical Development Plan

# in Figure	**69**
Variable Abbreviation	**HSE z2**
Variable Name	Housing for Zone 2
Variable Type	State
Variable Definition	= 'Initial Housing z2'
Base Value	= 352
Units	Hse
Additional Comments	See discussion in Chap 5 and Physical Development Plan

APPENDIX 1 (continued)

# in Figure	**70**
Variable Abbreviation	**HHS z2**
Variable Name	Household Size for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 4
Units	Ppl/hse
Additional Comments	Sources in Chap 5 and Physical Development Plan

# in Figure	**71**
Variable Abbreviation	**LFO z2**
Variable Name	Land Fraction Occupied for Zone 2
Variable Type	Auxiliary
Variable Definition	=(('BSTR z2'*'LPBS z2')+('HSE z2'*'LPH z2'))/'New Area z2'
Base Value	calculated
Units	area
Additional Comments	

# in Figure	**72**
Variable Abbreviation	**HDR z2**
Variable Name	Housing Demolition Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'HSE z2'*'new HDN z2'
Base Value	Calculated
Units	hse/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**73**
Variable Abbreviation	**LPH z2**
Variable Name	Land Per House in Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.25
Units	Acre/hse
Additional Comments	4 houses per acre, see chapter 5

# in Figure	**74**
Variable Abbreviation	**NEW HDN z2**
Variable Name	New Housing Demolition Normal with Risk
Variable Type	Auxiliary
Variable Definition	= 'Copy of IHND z1'*'Copy of z1 demo if'
Base Value	= calculated
Units	1/year
Additional Comments	

# in Figure	**75**
Variable Abbreviation	**Copy of z1 Demo if**
Variable Name	Effect of Risk on Housing Demolition
Variable Type	Auxiliary
Variable Definition	= IF('Rat z2'>.6<<risk_unit>>,3,1)
Base Value	Calculated
Units	dimensionless
Additional Comments	Impact of realized risk on housing in zone 2

APPENDIX 1 (continued)

# in Figure	**76**
Variable Abbreviation	**COPY of IHND z1**
Variable Name	Initial Housing Demolition Normal for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.025
Units	1/year
Additional Comments	Demolition Normal of 25 per 1000 see chapter 5

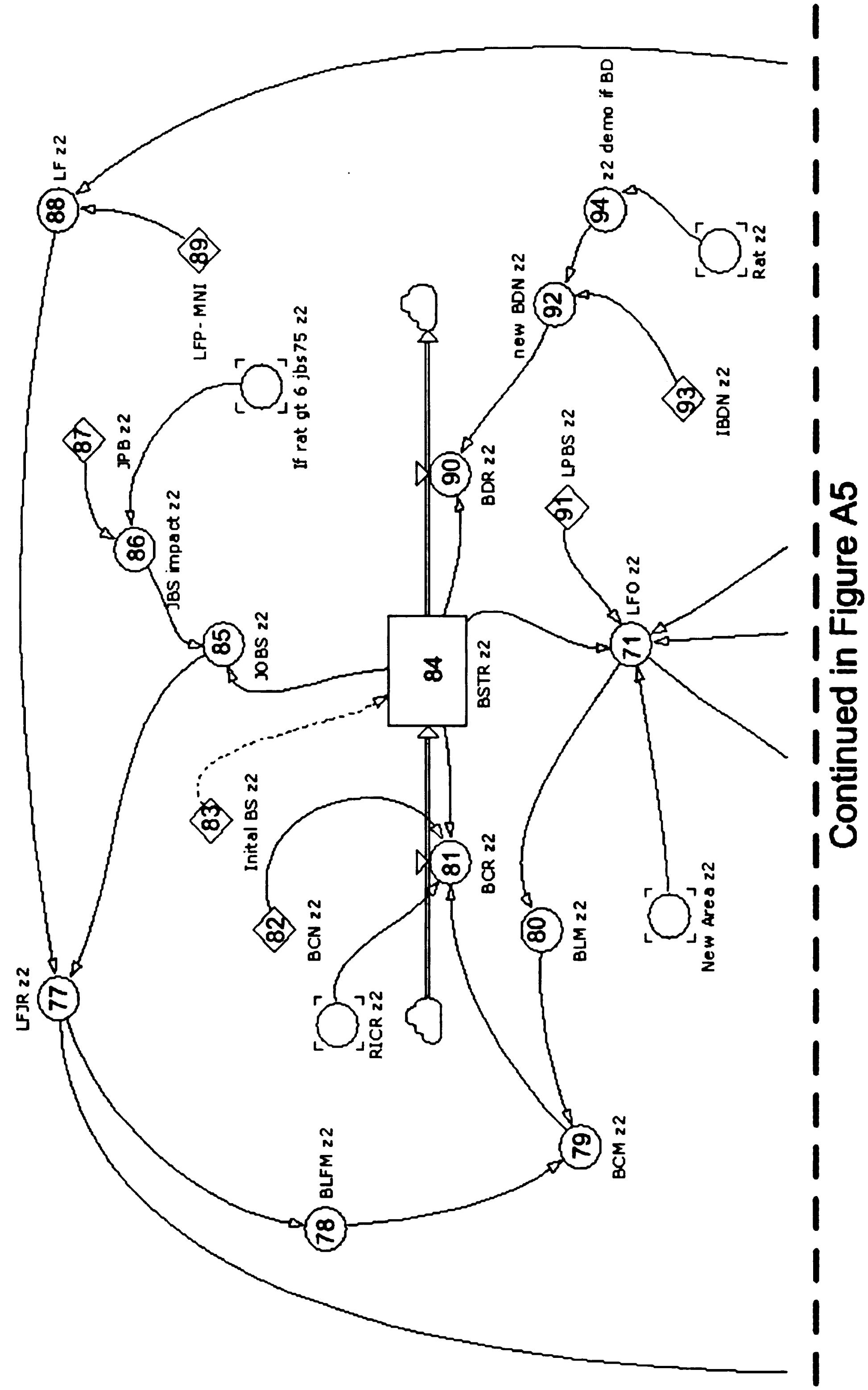


Figure A6. Business Structure Component for Zone 2

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A6. Description of Model Components in Figure A6

# in Figure	**77**
Variable Abbreviation	**LFJR z2**
Variable Name	Labor Force to Jobs Ratio for Zone 2
Variable Type	Auxiliary
Variable Definition	= 'LF z2'/'JOBS z2'
Base Value	Calculated
Units	dimensionless
Additional Comments	
# in Figure	**78**
Variable Abbreviation	**BLFM z2**
Variable Name	Business Labor Force Multiplier
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('LFJR z2',0,.2,{.2,.25,.35,.5,.7,1,1.35,1.6, 1.8,1.95//Min:0;Max:2//})
Base Value	Calculated
Units	n/a
Additional Comments	From urban model

APPENDIX 1 (continued)

# in Figure	**79**
Variable Abbreviation	**BCM z2**
Variable Name	Business Construction Multiplier for zone 2
Variable Type	Auxiliary
Variable Definition	'BLM z2'*'BLFM z2'
Base Value	Calculated
Units	dimensionless
Additional Comments	
# in Figure	**80**
Variable Abbreviation	**BLM z2**
Variable Name	Business Land Multiplier for Zone 2
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('LFO z2',0,.1,{1,1.15,1.3,1.4,1.45,1.40,1.3,.90, .5,.250,0//Min:0;Max:1.5//})
Base Value	Calculated
Units	n/a
Additional Comments	From urban model
# in Figure	**81**
Variable Abbreviation	**BCR z2**
Variable Name	Business Construction Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'BSTR z2'*'BCN z2'*'BCM z2'*'RICR z2'
Base Value	Calculated
Units	Bstr/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**82**
Variable Abbreviation	**BCN z2**
Variable Name	Business Construction Normal for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	=0.008
Units	1/year
Additional Comments	Value of 8 per 1000, see chapter 5 for assumptions

# in Figure	**83**
Variable Abbreviation	**Initial BS z2**
Variable Name	Initial Business Structures for Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 16
Units	bstr
Additional Comments	See chapter 5 for discussion of this value

# in Figure	**84**
Variable Abbreviation	**BSTR z2**
Variable Name	Business Structures in Zone 2
Variable Type	State
Variable Definition	= 'Initial BS z2'
Base Value	= 16
Units	Bstr
Additional Comments	See chapter 5 for discussion of this value

APPENDIX 1 (continued)

# in Figure	**85**
Variable Abbreviation	**Jobs z2**
Variable Name	Jobs in Zone 2
Variable Type	Auxiliary
Variable Definition	= 'BSTR z2'*'JBS impact z2'
Base Value	Calculated
Units	Jobs
Additional Comments	

# in Figure	**86**
Variable Abbreviation	**JBS impact z2**
Variable Name	Initial Housing z2 for zone 2
Variable Type	Auxiliary
Variable Definition	= 'If rat gt 6 jbs75 z2'*'JPB z2'
Base Value	Calculated
Units	Jobs/bstr
Additional Comments	Impact of risk on jobs

# in Figure	**87**
Variable Abbreviation	**JPBS z2**
Variable Name	Jobs per Business Structure in Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 25
Units	Jobs / bstr
Additional Comments	See Chap 5 for a discussion of this value

APPENDIX 1 (continued)

# in Figure	**88**
Variable Abbreviation	**LF z2**
Variable Name	Labor force in Zone 2
Variable Type	Auxiliary
Variable Definition	= 'POP z2'*'LFP- MNI'
Base Value	Calculated
Units	jobs
Additional Comments	

# in Figure	**89**
Variable Abbreviation	**LFP - MNI**
Variable Name	Labor Force Participation for Montserrat
Variable Type	Constant
Variable Definition	n/a
Base Value	= .60
Units	n/a
Additional Comments	Sources CIA Factbook, 1995 MNI Economic Dev. Plan

# in Figure	**90**
Variable Abbreviation	**BDR z2**
Variable Name	Business Demolition Rate for Zone 2
Variable Type	Rate
Variable Definition	= 'BSTR z2'*'new BDN z2'
Base Value	calculated
Units	Bstr/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**91**
Variable Abbreviation	**LPBS z2**
Variable Name	Land Per Business Structure in Zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 1.0
Units	Acre/bstr
Additional Comments	1 business structure per acre, see chap 5 for discussion
# in Figure	**92**
Variable Abbreviation	**NEW BDN z2**
Variable Name	New Business Demolition Normal with Risk in zone 2
Variable Type	Auxiliary
Variable Definition	= 'IBDN z2'*'z2 demo if BD'
Base Value	= calculated
Units	1/year
Additional Comments	
# in Figure	**93**
Variable Abbreviation	**IBDN z2**
Variable Name	Initial Business Demolition Normal in zone 2
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.025
Units	1/year
Additional Comments	See chapter 5 for a discussion of this value

# in Figure	**94**
Variable Abbreviation	**Z2 demo if BD**
Variable Name	Initial Housing Demolition Normal for Zone 2
Variable Type	Auxiliary
Variable Definition	= IF('Rat z2'>.6<<risk_unit>>,3,1)
Base Value	calculated
Units	n/a
Additional Comments	Action of risk threshold on business structures

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A7. Description of Model Components in Zone 3

Note: The Urban Component of the Model for Zone 3 is similar to Population Component of Zone 2 (Figure A4 and Table A4), the housing component of Zone 2 (Figure A5 and Table A5), and the business structure component of Zone 2 (Figure A6 and Table A6).

Rather than duplicate those figures and tables with a parallel structure, the table below list only the variables which have a different value for Zone 3.

Variable in Zone 3	Unique Zone 3 Values
Initial Population	2,110 people
Area	3,668 acres
Initial Houses	528 houses
Housing Construction Normal	0.4 1/year
Housing Demolition Normal	0.02 1/year
Household Size	5 persons per house
Land Per House	0.25 acres per house
Initial Business Structures	230 business structures
Business Construction Normal	0.01 1/year
Business Demolition Normal	0.006 1/year
Jobs Per Business Structure	5 jobs
Land Per Business Structure	0.17 acres per business structure

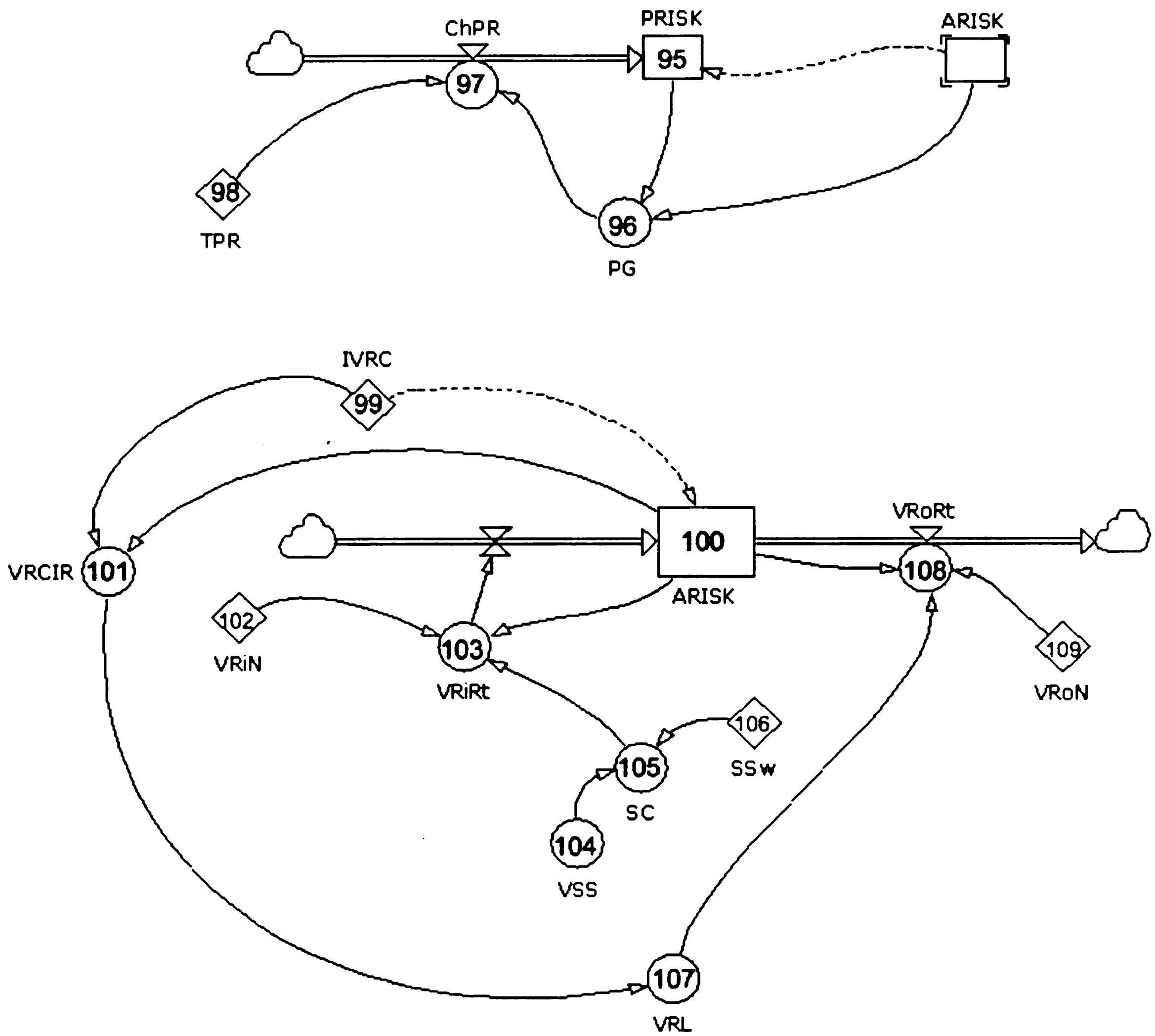


Figure A8. Actual and Perceived Risk Component for Entire Model

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A8. Description of Model Components in Figure A8

# in Figure	**95**
Variable Abbreviation	**PRISK**
Variable Name	Perceived Risk
Variable Type	State
Variable Definition	= 'ARISK'
Base Value	0.2
Units	risk unit
Additional Comments	See figure 45 for source of risk values
# in Figure	**96**
Variable Abbreviation	**PG**
Variable Name	Perception Gap
Variable Type	Auxiliary
Variable Definition	= ARISK-PRISK
Base Value	Calculated
Units	Risk unit
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**97**
Variable Abbreviation	**ChPR**
Variable Name	Change in Perceived Risk
Variable Type	Rate
Variable Definition	= PG/TPR
Base Value	Calculated
Units	risk unit / year
Additional Comments	
# in Figure	**98**
Variable Abbreviation	**TPR**
Variable Name	Time to Perceive Risk
Variable Type	Constant
Variable Definition	n/a
Base Value	= 5
Units	Years
Additional Comments	See risk discussion in chapter 5
# in Figure	**99**
Variable Abbreviation	**IVRC**
Variable Name	Initial Volcanic Risk Capacity
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.2
Units	Risk unit
Additional Comments	See figure 45 for source of risk values

APPENDIX 1 (continued)

# in Figure	**100**
Variable Abbreviation	**ARISK**
Variable Name	Actual Risk
Variable Type	State
Variable Definition	='IVRC'
Base Value	= 0.2
Units	risk unit
Additional Comments	See figure 45 for source of risk values

# in Figure	**101**
Variable Abbreviation	**VRCIR**
Variable Name	Actual Risk Ratio
Variable Type	Auxiliary - ratio
Variable Definition	= ARISK/IVRC
Base Value	Calculated
Units	dimensionless
Additional Comments	

# in Figure	**102**
Variable Abbreviation	**VRin**
Variable Name	Volcano Risk in
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.0215
Units	1/year
Additional Comments	Value mathematically set by testing to simulate natural forces

APPENDIX 1 (continued)

# in Figure	**103**
Variable Abbreviation	**VRiRt**
Variable Name	Volcano Rate in
Variable Type	Rate
Variable Definition	= (VRiN*ARISK)+SC
Base Value	Calculated
Units	Risk unit / year
Additional Comments	
# in Figure	**104**
Variable Abbreviation	**VSS**
Variable Name	Initial Housing z2 for zone 2
Variable Type	Auxiliary – step function
Variable Definition	= STEP(.04<<risk_unit>>,STARTTIME +10 <<yr>>) + STEP (-.01<<risk_unit>>,STARTTIME +20<<yr>>)
Base Value	Calculated
Units	Risk units
Additional Comments	Step function to simulate variations in volcano risk
# in Figure	**105**
Variable Abbreviation	**SC**
Variable Name	Step Function Output
Variable Type	Auxiliary
Variable Definition	= VSS*SSw
Base Value	Calculated
Units	Risk unit / year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**106**
Variable Abbreviation	**SSw**
Variable Name	Step Switch
Variable Type	Constant
Variable Definition	n/a
Base Value	1
Units	n/a
Additional Comments	Switch , off=0 and on=1

# in Figure	**107**
Variable Abbreviation	**VRL**
Variable Name	Volcano Risk Limit
Variable Type	Auxiliary – Table function
Variable Definition	GRAPH(VRCIR,0,1,{0.027,0.043,0.085,0.128,0.174,0.213,0.248, 0.29,0.337,0.395,0.49//Min:0;Max:0.6//})
Base Value	Calculated
Units	n/a
Additional Comments	

# in Figure	**108**
Variable Abbreviation	**VRoRt**
Variable Name	Volcano Risk Out Rate
Variable Type	Rate
Variable Definition	= (ARISK*VRoN)*VRL
Base Value	calculated
Units	Risk unit/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**109**
Variable Abbreviation	**VRoN**
Variable Name	Volcano Risk Out Normal
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.5
Units	1/year
Additional Comments	Value mathematically set by testing to simulate natural forces

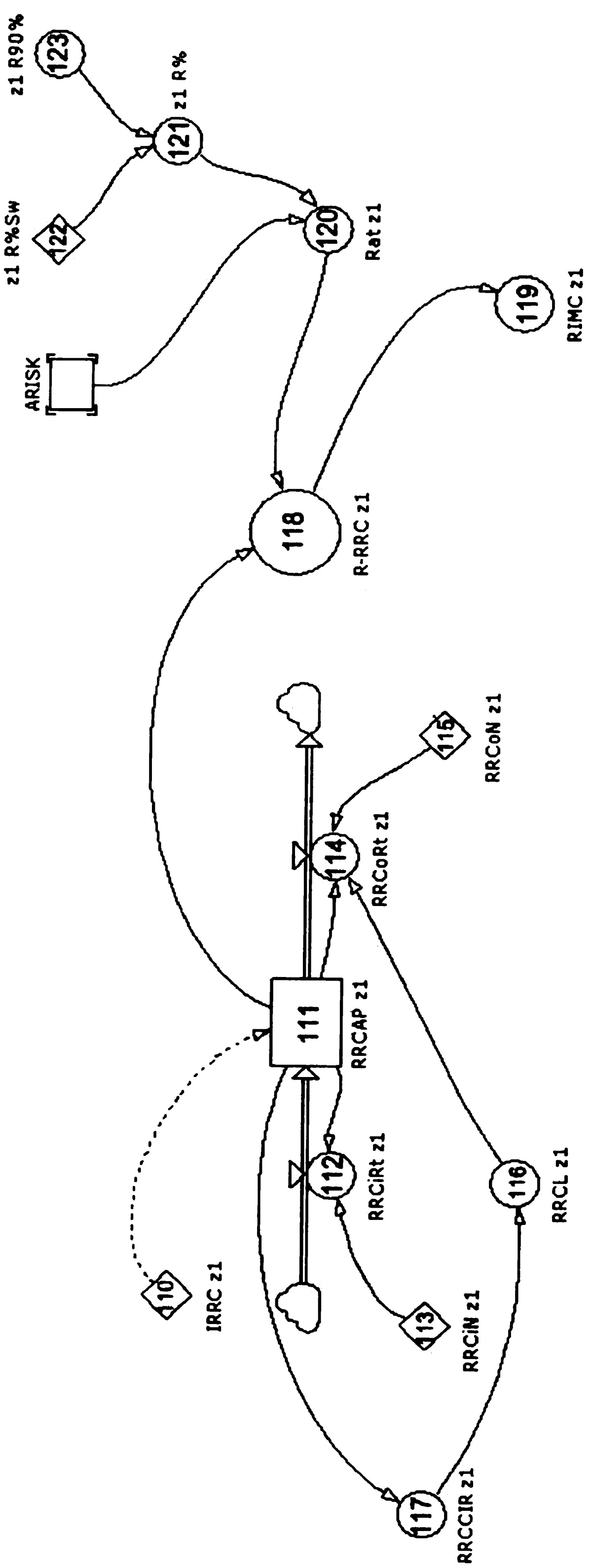


Figure A9. Risk as Realized by Zone for Zone 1

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A9. Description of Model Components in Figure A9

# in Figure	**110**
Variable Abbreviation	**IRRC z1**
Variable Name	Initial Risk Reduction Capacity for zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.1
Units	risk unit
Additional Comments	Set by testing to simulate a level of mitigation
# in Figure	**111**
Variable Abbreviation	**RRCAP z1**
Variable Name	Risk Reduction Capacity for zone 1
Variable Type	State
Variable Definition	= 'IRRC z1'
Base Value	=0.1
Units	Risk unit
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**112**
Variable Abbreviation	**RRCiRt**
Variable Name	Risk Reduction Capacity Increase Rate for Zone 1
Variable Type	Rate
Variable Definition	= 'RRCiN z1'*'RRCAP z1'
Base Value	Calculated
Units	risk unit / year
Additional Comments	

# in Figure	**113**
Variable Abbreviation	**RRCiN z1**
Variable Name	Risk Reduction Capacity Increase Normal for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 0.048
Units	1/year
Additional Comments	Set by testing to simulate a level of mitigation

# in Figure	**114**
Variable Abbreviation	**RRCoRt z1**
Variable Name	Risk Reduction Capacity Decrease for Zone 1
Variable Type	Rate
Variable Definition	= ('RRCAP z1'*'RRCoN z1')*'RRCL z1'
Base Value	Calculated
Units	Risk unit/year
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**115**
Variable Abbreviation	**RRCoN z1**
Variable Name	Risk Reduction Capacity Decrease Normal for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	= 1.3
Units	1/year
Additional Comments	Set by testing to simulate a level of mitigation

# in Figure	**116**
Variable Abbreviation	**RRCL z1**
Variable Name	Risk Reduction Capacity Limit for Zone 1
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('RRCCIR z1',0,1,{.01,.015,.02,.025,.04,0.075,.11, 0.165, 0.25,0.4,0.5//Min:0;Max:0.6//})
Base Value	Calculated
Units	n/a
Additional Comments	

# in Figure	**117**
Variable Abbreviation	**RRCCIR z1**
Variable Name	Ratio of Risk Reduction to Initial Risk Reduction Zone 1
Variable Type	Auxiliary – ratio
Variable Definition	= 'RRCAP z1'/'IRRC z1'
Base Value	Calculated
Units	Dimensionless
Additional Comments	

# in Figure	**118**
Variable Abbreviation	**R-RRC z1**
Variable Name	Ratio of Actual Risk to Risk Reduction Capacity for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'Rat z1'/'RRCAP z1'
Base Value	Calculated
Units	Dimensionless
Additional Comments	
# in Figure	**119**
Variable Abbreviation	**RIMC z1**
Variable Name	Risk Impact on Construction for Zone 1
Variable Type	Auxiliary – table function
Variable Definition	= GRAPH('R-RRC z1',0,.2,{1.95,1.82,1.5,1.27,1.11,1,0.61, 0.39,0.26,0.18,0.11//Min:0;Max:2.5;Zoom//})
Base Value	Calculated
Units	n/a
Additional Comments	Table functions takes risk by action to urban model
# in Figure	**120**
Variable Abbreviation	**RAT z1**
Variable Name	Risk Realized at Zone 1
Variable Type	Auxiliary
Variable Definition	= ARISK*'z1 R%'
Base Value	Calculated
Units	Risk unit
Additional Comments	

APPENDIX 1 (continued)

# in Figure	**121**
Variable Abbreviation	**z1 R%**
Variable Name	Realized Risk Value for Zone 1
Variable Type	Auxiliary
Variable Definition	= 'z1 R%Sw'*'z1 R90%'
Base Value	Calculated
Units	Dimensionless
Additional Comments	
# in Figure	**122**
Variable Abbreviation	**Z1 R%Sw**
Variable Name	Risk Realized Switch for Zone 1
Variable Type	Constant
Variable Definition	n/a
Base Value	=1
Units	Dimensionless
Additional Comments	Switch, on=1 and 0ff=0
# in Figure	**123**
Variable Abbreviation	**Z1 R90%**
Variable Name	Percent of Risk Realized at Zone 1
Variable Type	Auxiliary
Variable Definition	= 0.90
Base Value	n/a
Units	Dimensionless
Additional Comments	Measured as a % of Actual Risk

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A10. Risk as Realized in Zone 2 Components

Note: The Risk as Realized in Zone 2 Component of the Model is Similar to the Risk as Realized by Zone 1 Component (Figure A9 and Table A9).

Rather than duplicate those figures and tables with a parallel structure, the table below list only the variables which have a different value for Zone 2.

Variable in Zone 2	Unique Zone 2 Values
Risk Reduction Capacity Increase	0.98 1/year
Percent of Risk Realized at Zone 2	80 %

APPENDIX 1 (Continued)

MONTSERRAT URBAN AND RISK MODEL
DETAIL OF MODEL COMPONENTS

Table A11. Risk as Realized in Zone 3 Components

Note: The Risk as Realized in Zone 3 Component of the Model is Similar to the Risk as Realized by Zone 1 Component (Figure A9 and Table A9).

Rather than duplicate those figures and tables with a parallel structure, the table below list only the variables which have a different value for Zone 3.

Variable in Zone 3	Unique Zone 3 Values
Risk Reduction Capacity Increase	0.22 1/year
Percent of Risk Realized at Zone 3	70 %

APPENDIX 2

URBAN MODEL HOUSING MULTIPLIERS

Appendix 2 provides graphs depicting the values of the multipliers in the housing component of the urban model. The multipliers are important as they reflect push and pull influences in the Montserrat Urban and Risk Model. The source for these multipliers is the POPHOU urban model as developed by Alfeld and Graham (Alfeld and Graham, 1976) based on Forrester's work (Forrester, 1969).

- **Figure B1** depicts the Housing Attractiveness Multiplier values graph.
- **Figure B2** depicts the Housing Land Multiplier values graph.
- **Figure B3** depicts the Attractiveness of Housing Multiplier values graph.

APPENDIX 2 (Continued)

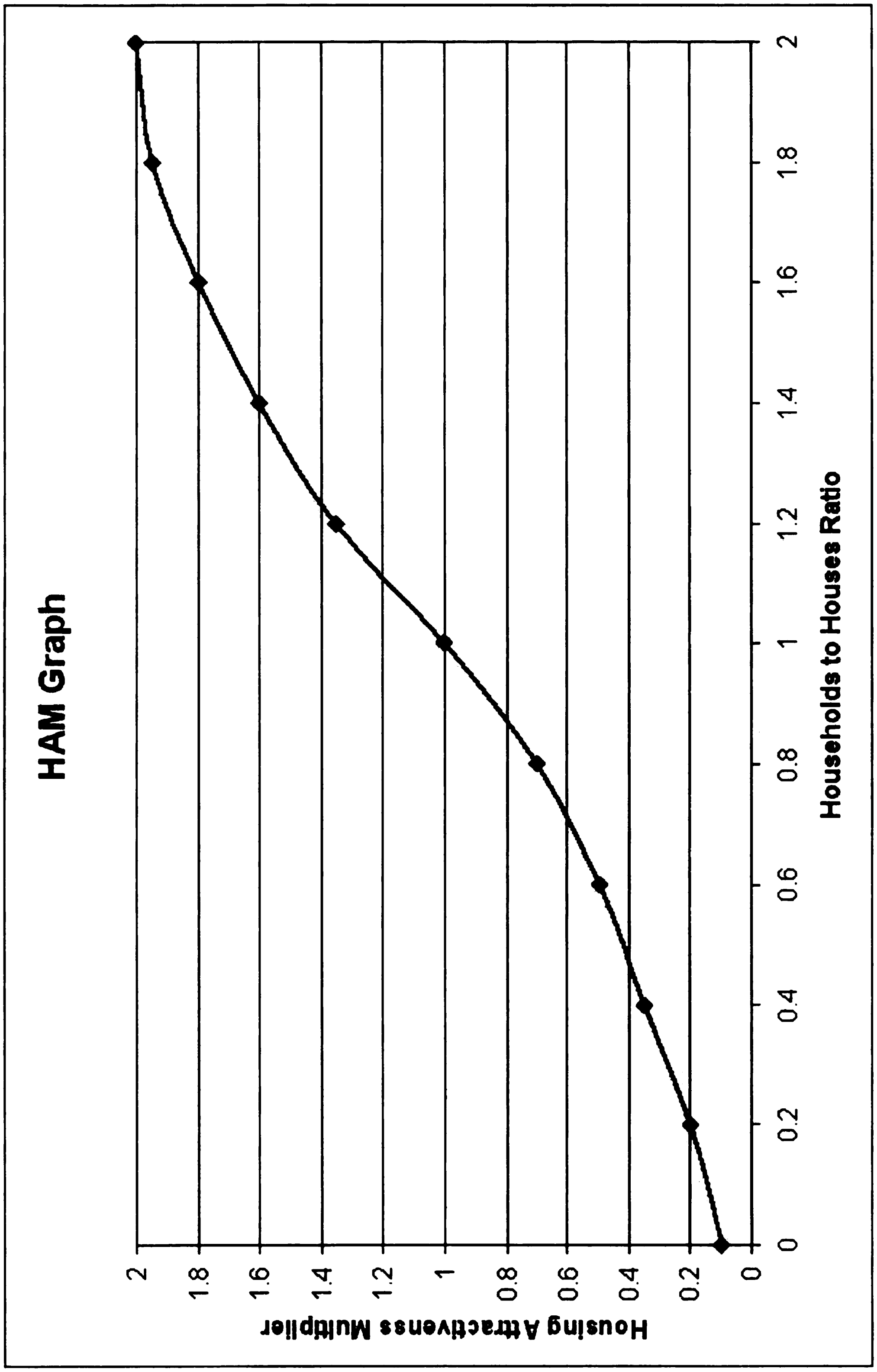


Figure B1. Housing Attractiveness Multiplier Values

APPENDIX 2 (Continued)

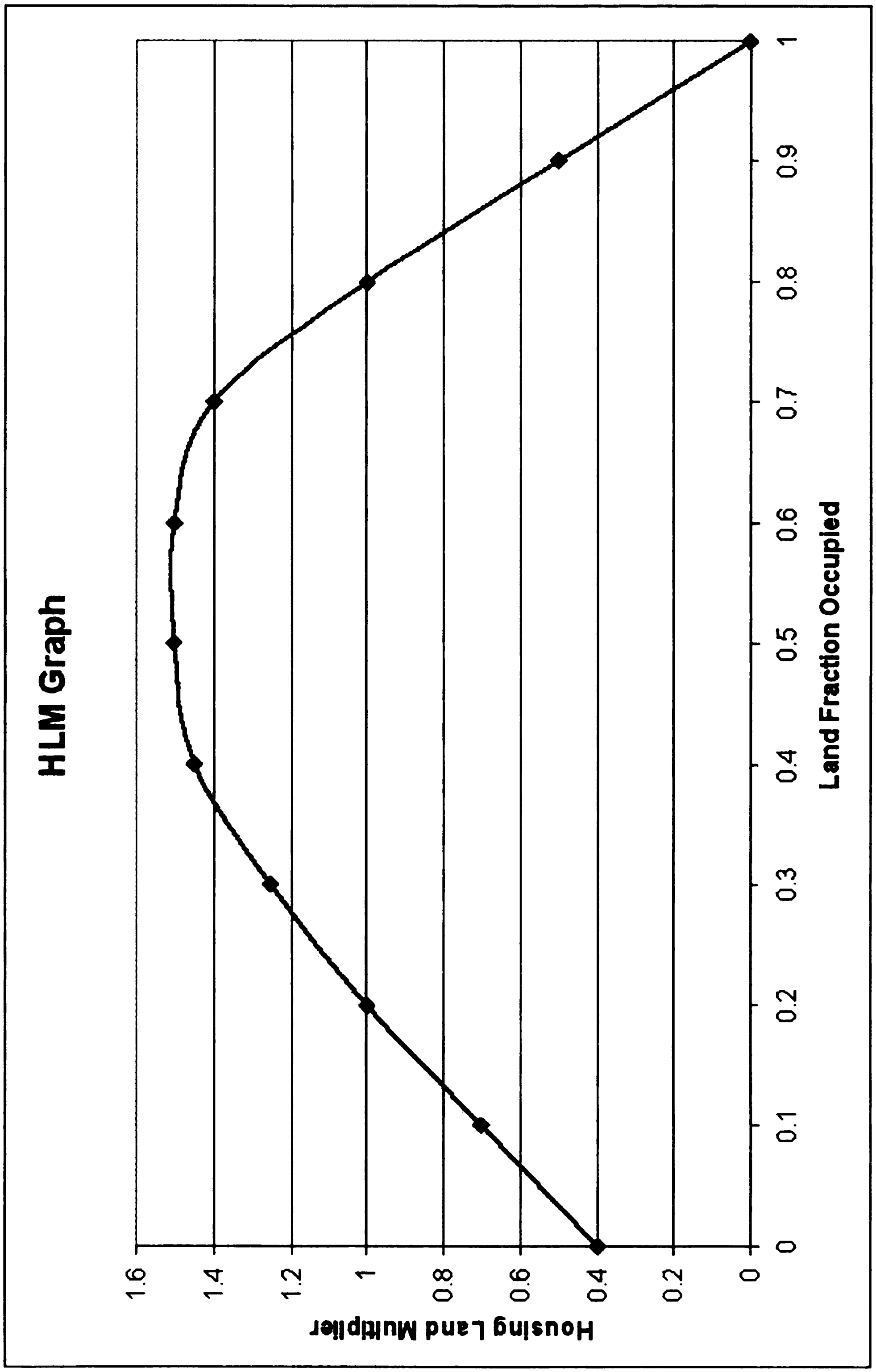


Figure B2. Housing Land Multiplier Values

APPENDIX 2 (Continued)

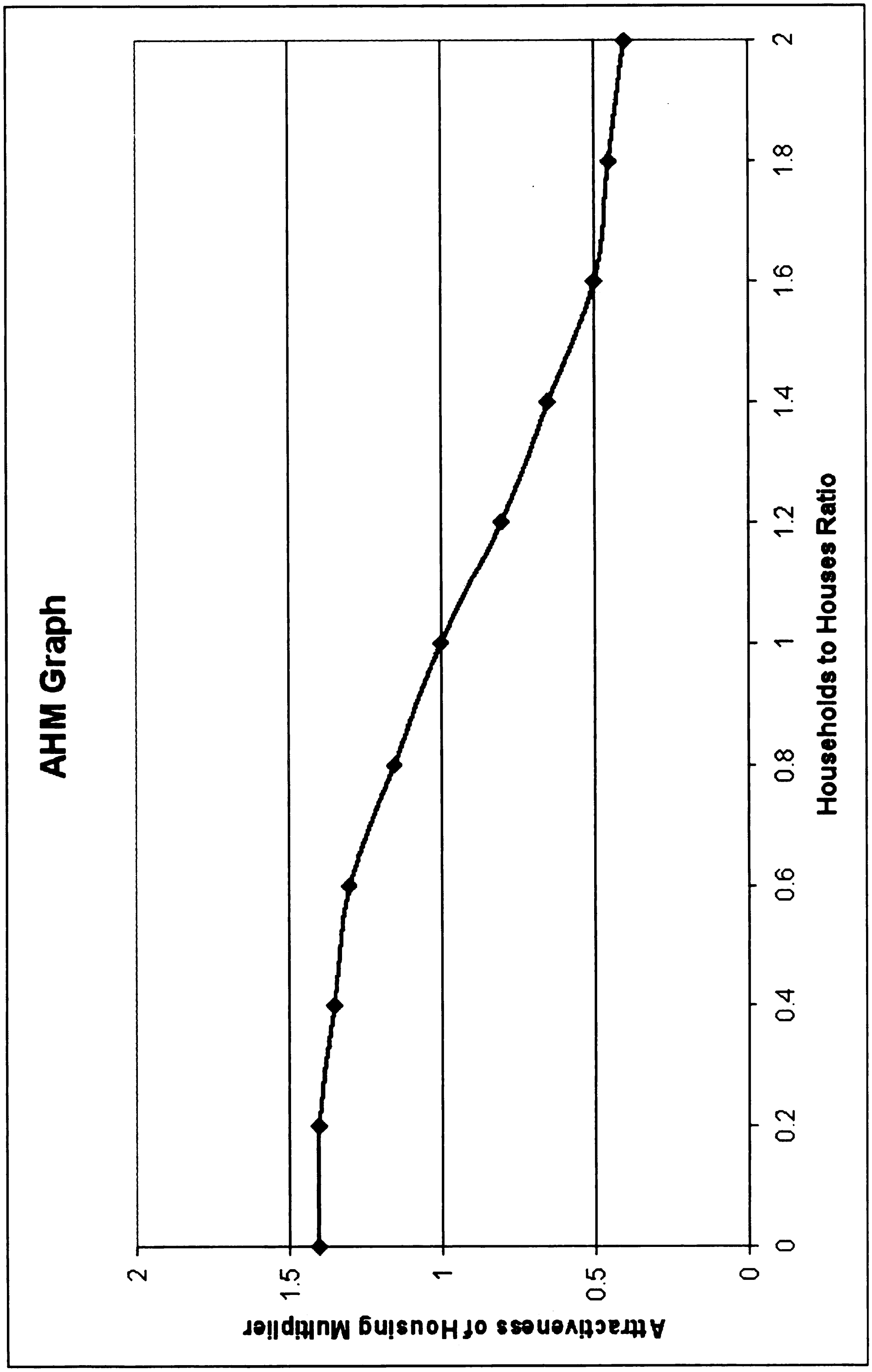


Figure B3. Attractiveness of Housing Multiplier Values

APPENDIX 3

URBAN MODEL BUSINESS MULTIPLIERS

Appendix 3 provides graphs depicting the values of the multipliers in the business structures component of the urban model. The multipliers are important as they reflect push and pull influences in the Montserrat Urban and Risk Model. The source for these multipliers is the BSNSS2 urban model as developed by Alfeld and Graham (Alfeld and Graham, 1976) based on Forrester's work (Forrester, 1969).

- **Figure C1** depicts the Business Land Multiplier values graph.
- **Figure C2** depicts the Business Labor Force Multiplier values graph.
- **Figure C3** depicts the Attractiveness of Jobs Multiplier values graph.

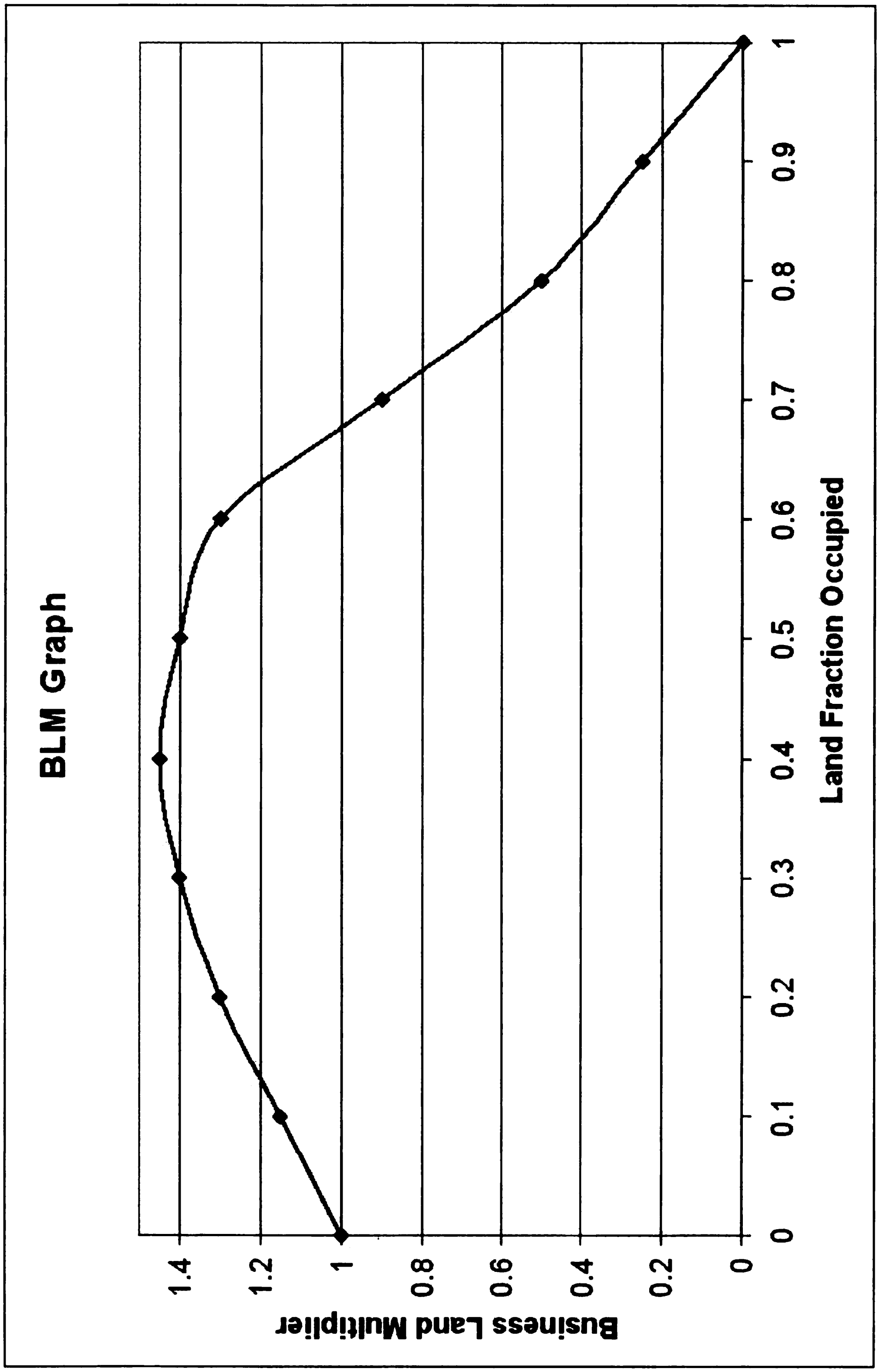


Figure C1. Business Land Multiplier Values

APPENDIX 3 (Continued)

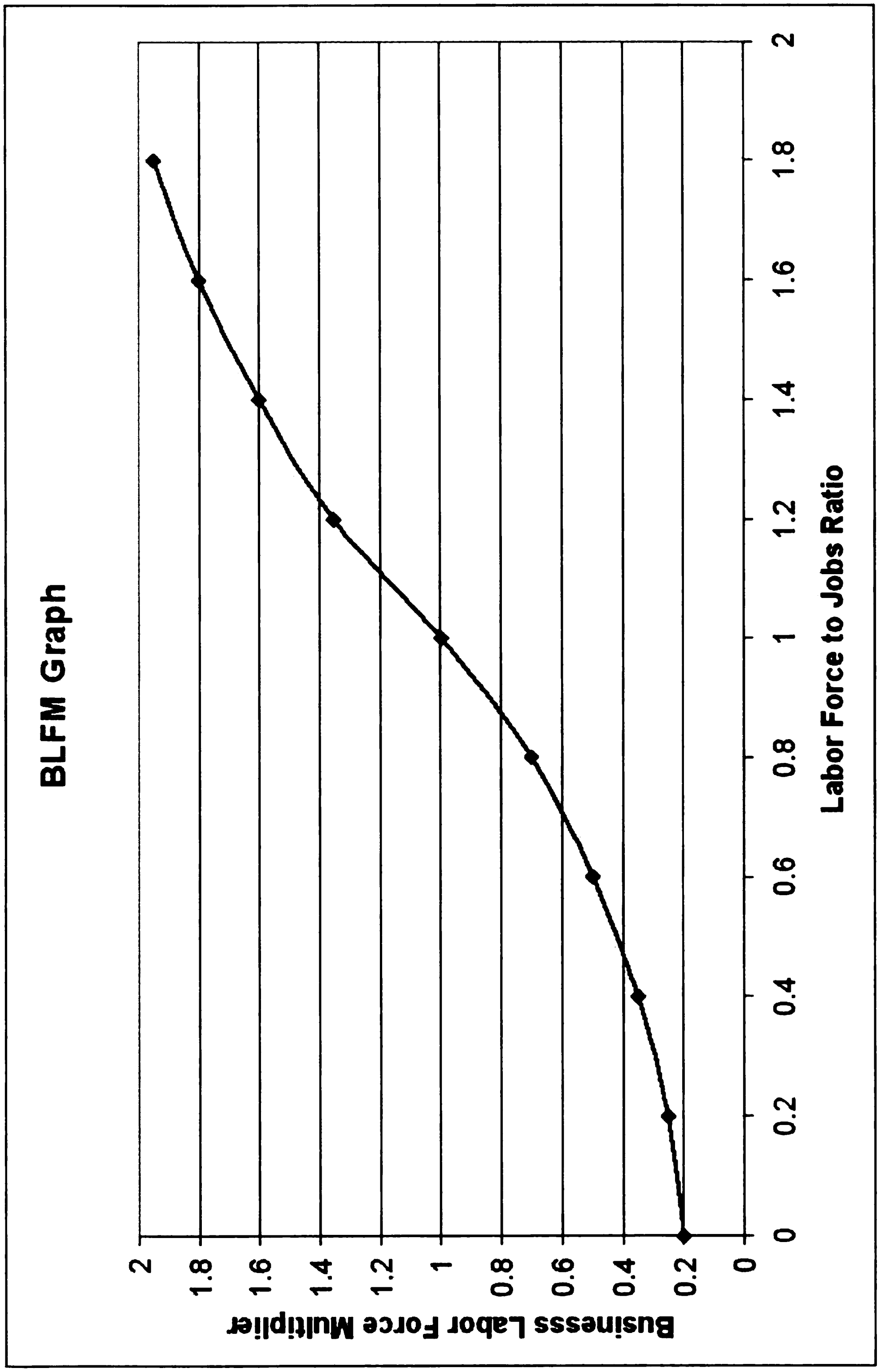


Figure C2. Business Labor Force Multiplier Values

APPENDIX 3 (Continued)

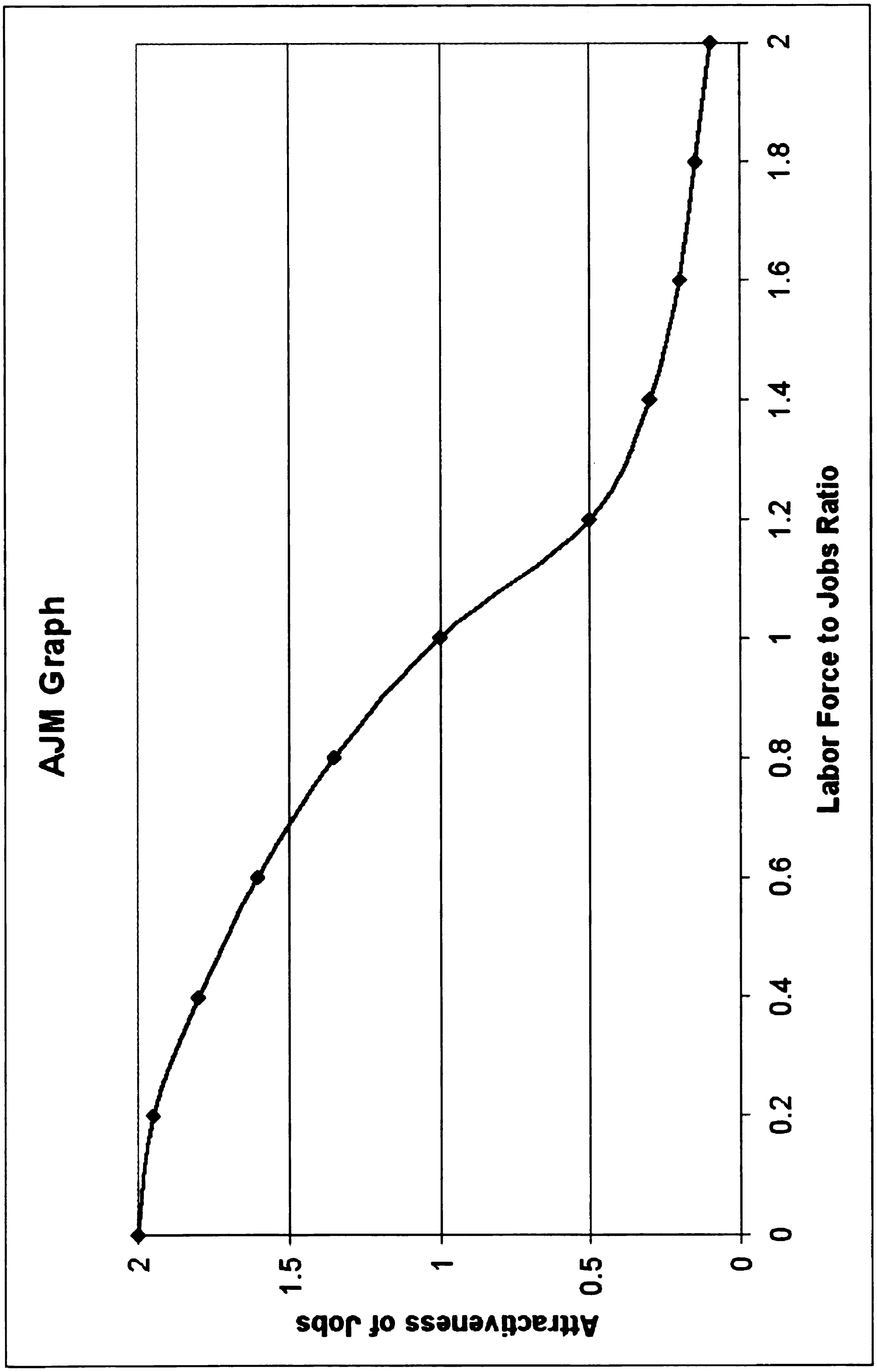


Figure C3. Attractiveness of Jobs Multiplier Values

APPENDIX 4

MODEL OUTPUT: POPULATION TABLES

Appendix 4 provides tables depicting population values over time for each of the four scenarios. As the question being asked in this study is: "Is the post-disaster redevelopment goal for Montserrat of reaching a population of 10,000 persons feasible given development constraints and continued risk?" the population output values are an important part of the results. These results are also depicted graphically in Chapter 6. This author suggests that Figures D2 and D3 represent the most feasible redevelopment scenarios.

- **Figure D1** depicts the model's output for the population state variables using the base – low risk scenario.

- **Figure D2** depicts the model's output for the population state variables using the medium risk scenario.

- **Figure D3** depicts the model's output for the population state variables using the medium risk with step scenario.

- **Figure D4** depicts the model's output for the population state variables using the high risk scenario.

APPENDIX 4 (Continued)

Total Population Table

Time	POP MNI (ppl)
Jan 01, 2005	4,690
Jan 01, 2010	5,146
Jan 01, 2015	5,606
Jan 01, 2020	6,156
Jan 01, 2025	6,814
Jan 01, 2030	7,579
Jan 01, 2035	8,288
Jan 01, 2040	8,806
Jan 01, 2045	9,260
Jan 01, 2050	9,700
Jan 01, 2055	10,137

Non-Commercial Use Only

Population by Zone Table

Time	POP z1	POP z2	POP z3
Jan 01, 2005	1,173	1,407	2,110
Jan 01, 2010	1,118	1,610	2,418
Jan 01, 2015	1,070	1,845	2,691
Jan 01, 2020	1,028	2,111	3,017
Jan 01, 2025	992	2,398	3,425
Jan 01, 2030	960	2,702	3,917
Jan 01, 2035	931	3,021	4,337
Jan 01, 2040	904	3,356	4,546
Jan 01, 2045	878	3,708	4,674
Jan 01, 2050	854	4,076	4,769
Jan 01, 2055	831	4,462	4,844

Non-Commercial Use Only

Table D1. Population Tables for SCENARIO A: Low Risk

Total Population Table

Time	POP MNI (ppl)
Jan 01, 2005	4,690
Jan 01, 2010	5,133
Jan 01, 2015	5,538
Jan 01, 2020	5,982
Jan 01, 2025	6,499
Jan 01, 2030	7,083
Jan 01, 2035	7,640
Jan 01, 2040	7,919
Jan 01, 2045	8,078
Jan 01, 2050	7,817
Jan 01, 2055	7,348

Population by Zone Table

Time	POP z1	POP z2	POP z3
Jan 01, 2005	1,173	1,407	2,110
Jan 01, 2010	1,118	1,606	2,409
Jan 01, 2015	1,068	1,809	2,660
Jan 01, 2020	1,022	2,026	2,934
Jan 01, 2025	980	2,271	3,248
Jan 01, 2030	941	2,544	3,599
Jan 01, 2035	795	2,916	3,928
Jan 01, 2040	551	3,268	4,101
Jan 01, 2045	382	2,983	4,713
Jan 01, 2050	265	2,403	5,148
Jan 01, 2055	185	1,922	5,241

Table D2. Population Tables for SCENARIO B: Medium Risk

Total Population Table

Time	POP MNI (ppl)
Jan 01, 2005	4,690
Jan 01, 2010	5,141
Jan 01, 2015	5,579
Jan 01, 2020	6,095
Jan 01, 2025	6,663
Jan 01, 2030	7,267
Jan 01, 2035	7,551
Jan 01, 2040	7,719
Jan 01, 2045	7,481
Jan 01, 2050	7,040
Jan 01, 2055	6,522

Population by Zone Table

Time	POP z1	POP z2	POP z3
Jan 01, 2005	1,173	1,407	2,110
Jan 01, 2010	1,118	1,608	2,415
Jan 01, 2015	1,069	1,831	2,679
Jan 01, 2020	1,025	2,089	2,982
Jan 01, 2025	984	2,360	3,319
Jan 01, 2030	785	2,803	3,680
Jan 01, 2035	544	3,143	3,864
Jan 01, 2040	377	2,719	4,623
Jan 01, 2045	262	2,200	5,019
Jan 01, 2050	182	1,766	5,092
Jan 01, 2055	127	1,409	4,986

Table D3. Population Tables for SCENARIO C: Medium Risk w/ Step

Total Population Table

Time	POP MNI (ppl)
Jan 01, 2005	4,690
Jan 01, 2010	5,130
Jan 01, 2015	5,520
Jan 01, 2020	5,930
Jan 01, 2025	6,383
Jan 01, 2030	6,690
Jan 01, 2035	6,710
Jan 01, 2040	4,718
Jan 01, 2045	3,875
Jan 01, 2050	3,329
Jan 01, 2055	2,886

Population by Zone Table

Time	POP z1	POP z2	POP z3
Jan 01, 2005	1,173	1,407	2,110
Jan 01, 2010	1,118	1,606	2,406
Jan 01, 2015	1,068	1,801	2,651
Jan 01, 2020	1,022	1,998	2,910
Jan 01, 2025	980	2,205	3,197
Jan 01, 2030	682	2,471	3,538
Jan 01, 2035	473	2,096	4,141
Jan 01, 2040	328	1,749	2,641
Jan 01, 2045	228	1,438	2,209
Jan 01, 2050	159	1,168	2,003
Jan 01, 2055	110	940	1,836

Table D4. Population Tables for SCENARIO D: High Risk

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