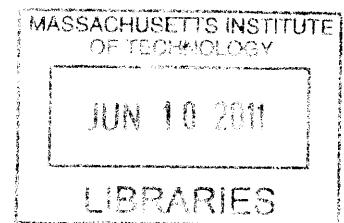


Modeling the Water Consumption of Singapore Using System Dynamics

by
Karen Noiva Welling



S.B. Mechanical Engineering, Massachusetts Institute of Technology (2008)

Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of
Master of Science in Building Technology

at the

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Author

.....
Department of Architecture
May 20, 2011

Certified by

John E. Fernández
Associate Professor of Architecture and Building Technology and
Engineering Systems
Thesis Supervisor

Accepted by

Takehiko Nagakura
Chair, Department Committee on Graduate Students

Thesis Advisor John E. Fernández, M.Arch.

Associate Professor of Architecture and Building Technology and Engineering Systems

Thesis Reader James Wescoat, Ph.D.

Aga Khan Professor

Thesis Reader Noelle Eckley Selin, Ph.D.

Assistant Professor of Engineering Systems and Atmospheric Chemistry

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Abstract

Water resources are essential to life, and in urban areas, the high demand density and finite local resources often engender conditions of relative water scarcity. To overcome this scarcity, governments intensify infrastructure and project demand into the future. Growth in the economy, population, and affluence of cities increase water demand, and water demand for many cities will increase into the future, requiring additional investments in water infrastructure. More sustainable policies for water will require capping socioeconomic water demand and reducing the associated demand for non-renewable energy and material resources.

The thesis consists of the formulation of a System Dynamics model to replicate historic trends in water consumption for the growing city of Singapore. The goal of the model is to provide a platform for assessing socioeconomic demand trends relative to current water resources and water management policies and for examining how changes in climate and infrastructure costs might impact water availability over time. The model was calibrated to historical behavior and scenarios examined the vulnerability of supply to changing demand, climate, and cost. The outcome is a qualitative dynamic assessment of the circumstances under which Singapore's current policies allow them to meet their goals. Singapore was chosen as the case study to demonstrate the methodology, but in the future, the model will be applied to other cities to develop a typology of cities relative to water resources.

Thesis Supervisor: John E. Fernández

Title: Associate Professor of Architecture and Building Technology and Engineering Systems



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0.1 Acknowledgments

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It could be better; it could be worse.

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Chapter 1

Introduction

1.1 Forward

What has been is what will be,
and what is done is what will be done;
and there is nothing new under the sun.

Is there a thing of which it is said,
 ”See, this is new?”
It has been already, the ages before us.
There is no remembrance of former things,
nor will there be any remembrance of later things yet to happen.

-Ecclesiastes 1:9-11, *The Bible*

J.R. McNeill introduces his book of environmental history, "Something New Under the Sun," with the preceding verses from Ecclesiastes, in order to set the stage to document the ways in which the interactions between society and the natural environment is beginning to enter new and uncharted territory. Although past civilizations have witnessed the pressures from a changing environment, never before have the resources consumed, metabolized, and excreted by society been on the order of magnitude with natural systems[25].

Current levels of resource consumption are considered unsustainable in a quantitative sense; currently, people consume more materials than are replenished. Even beyond this, however, material flows have reached the order of magnitude of global nutrient cycles [26]. People now

drive global material flows [27]. The risk of consumption continuing at that level or growing is the disruption and subsequent unpredictability of natural balancing loops, as exemplified by the effect of carbon dioxide on global temperatures and weather patterns.

1.1.1 Here There Be Dragons

As various limits are approached, nonlinearities always weaken the positive loops and strengthen the negative feedbacks until the exponential growth halts[21, p. 272].

Society's current demand for materials outstrips what nature can provide. There is evidence that these patterns of consumption have been undermining the carrying capacity of global natural resources, which if true would likely bring about large changes in the natural processes familiar to us. When known limits are reached, when boundaries are approached, known processes become unstable and unpredictable. The goal of wanting to manage resources sustainably while maintaining quality of life is an acknowledgement that remaining within a familiar operating regime for natural processes is preferable to setting a course for the unknown. Nature is a great balancer and is characterized by many negative feedback processes that act to keep the world in a dynamic equilibrium.

Sitting idly by while natural processes change in ways that are potentially detrimental to society is at odds with global governance and modern sensibilities. Given the rapid technological progress witnessed over the past few centuries, it seems possible that as a global society we find ways to dematerializing quality of life and mange our natural resources sustainably. To achieve that, it is necessary to know how resources contribute to quality of life and other social processes and also how consumption of these resources affects global resources overall. It requires an assessment of what quality of life means and how to achieve it, an accounting of physical goods and natural resources, and ultimately an assessment of what environmental impact has been incurred as well as how to ameliorate it.

The challenge of global sustainability is emerging as one of the most important issues of our

generation, and possibly generations to come[28]. Sustainable development is defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[29], and addresses the concern that because human extraction and excretion have reached the order of magnitude of natural nutrient cycling as well as natural stocks, that we are potentially undermining the sustainability of the way of life on which we depend[30].

1.1.2 Water Scarcity

Although freshwater is a renewable resource, water scarcity and water stress are emerging as modern issues and are one manifestation of the type of resource scarcity targeted by sustainability studies. Urban environments place large demand on local freshwater resources[31]. In addition to the challenges of establishing a sufficient supply, the role of water supplies in human health and sanitation have motivated advances in technology and governance, and has also played an important role in the expansion and densification of cities[32]. Even for modern cities, including some with more than 10 million residents, managing freshwater resources is relevant issue[33]. Water is essential to many urban processes such as the provision of life, the removal of waste and debris, and the support of industrial processes which create economic value[33].

In regions where water supply has been stable for a long time it is easy to assume that they will continue that way indefinitely[18]. Although many modern water systems are stable, they are still susceptible to disruption. Changing land use and climate may alter water supply characteristics, and urbanization changes water quality and demand[32]. Deteriorating infrastructure can disrupt water services to major metropolitan areas. Urban water systems and the decisions that govern them are complex. Water scarcity can arise anytime a change in one area is not compensated by a sufficient change in another area such that supply no longer is sufficient to meet demand.

It has been also been argued that water has not been properly valued in terms of the service it provides. It is essential for life, yet has little economic value. It supports ecosystems and

vegetation, but demands to support those biological systems are often not taken into account in urban policy[34]. Even when water is not free, its economic value is lower than its cultural and metabolic value. The issue is complicated though, by the fact that water may be considered a human right, in the same way that breathing air and the pursuit of happiness are a right. Common societal values often do not have an economic price, and in addition to being universally valued, it often has layers of cultural and aesthetic values. In scarcity, water accrues a greater economic value, but to wait for water scarcity to provide economic feedback is likely to give rise to instabilities.

1.2 Singapore: A Success Story for Sustainability Policy?

Singapore is a small city-state off of the coast of Malaysia (see Figure 1-1), and claimed for England by Sir Stamford Raffles in 1819 in hopes that it would come to rival the rich trading ports operated by the Netherlands elsewhere in the region. Early Singaporean commerce included trade and agriculture, which focused on high-maintenance cash crops. But from the earliest days, Singapore thrived as a trading post and by the early 1900s, trade was the primary form of economy and agriculture had mostly disappeared. Today, Singapore is one of the largest economies in the world, both in terms of size and affluence[20].

Singapore's commitment to advancing technologies to achieve a self-sufficient water supply has positioned it as a world leader in water supply technologies and policies. As such it presented an opportunity to examine water management through System Dynamics, a modeling paradigm particularly relevant to problems of management and decision-making. In examining the case of Singapore, we hoped to gain insight into the role ambitious financial and demand management played in water demand and supply.

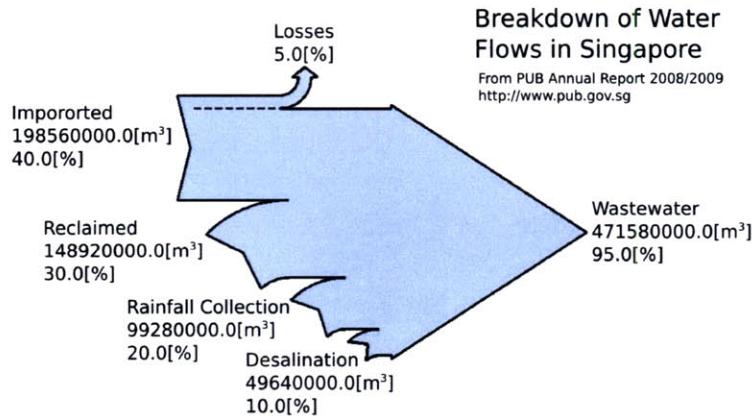
Currently, Singapore relies heavily on water from other countries. as an island nation, Singapore uses more water than falls to its surfaces. Because of this, Singapore is vulnerable to



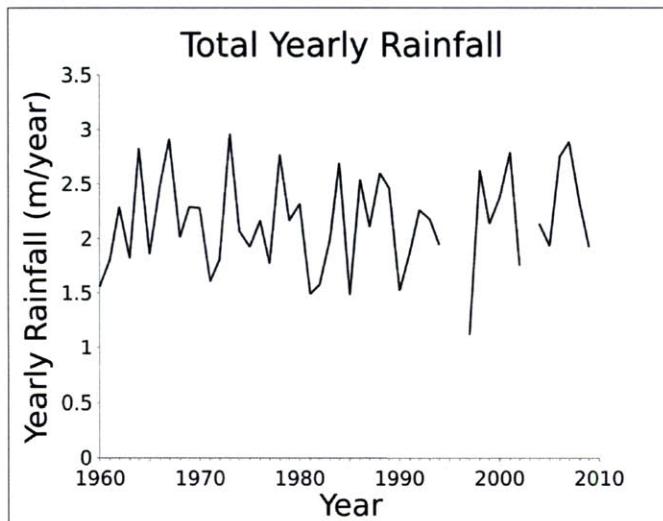
Figure 1-1: Map shows the location of Singapore relative to other southeast Asian countries[1].

changes in political climate as well as natural disasters that are outside of its control. Recognizing this, Singapore has committed to expanding its supply capacity in a way that make it more self-sufficient and has very carefully thought out its supply and demand strategies for the next 50 years. These plans include increasing catchment on the island of Singapore itself, increasing water reuse, increasing water conservation, and installing desalination capacity.

Although Singapore averages over two meters of precipitation each year (as seen in Figure 1-2(b), which is twice the global average of one meter per year, a limited catchment area and large socioeconomic water demand has caused the United Nations classify the country as one of the most water-scarce in the world: it is ranked 170th of 190 countries in terms of fresh water availability[20]. Water shortages in the early days of Singapore's independence made it clear that Singapore's ultimate success would depend on a sufficient water supply. From the time of those early water shortages, ensuring water supply has been a central part of Singapore's development strategy, combined with planning for electricity and fuel[20, 35].



(a) The main inflows and outflows of Singapore's water system



(b) Average yearly rainfall in Singapore

Figure 1-2: Water flows through Singapore and the yearly precipitation input over time (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

In 1964, the year after achieving independence from Great Britain in 1963, a severe drought reduced water supply to such low levels that rationing was implemented. These rationing policies were able to effect a demand reduction of 13.4%, but as soon as rationing stopped, demand immediately shot back up[20]. A drought in 1970 nearly required water rationing again, but expansion of water resources in the interim combined with return of heavy rains prevented that from happening[20].

In the interim, Singapore greatly increased the production, storage, and treatment capacity of its water infrastructure. At the time, water supply on Singapore drew from only a small

fraction of the total island area. Part of the reason for this was because much island area is low-lying and brackish. Additionally, a significant portion of the island was already developed and at the time could not be used as catchment.

Because of its limited internal supplies, in the 1970s the government began to push for advancements in desalination and reclamation technologies. The government also began to collect water from more of the island area through the use of new, material-intensive techniques which drained wetlands of brackish water, capped them off from marine inflow, and then refilled the area with freshwater. Singapore was able to install water collection infrastructure such that freshwater was collected from 50% of the island. The most ambitious project to expand island catchment area was finished in 2008. The Marina Barrage increased the catchment area to 67% up from 50% and cost S\$200 million¹.

The motivation for Singapore's ambitious approach to water supply and demand arises from the fact that over 50% of current water supply comes from Johore, Malaysia. A treaty from the period of independence, 1960 and 1961, established that that water be supplied at a low cost to Singaporeans. However, the government of Singapore view this source as uncertain. The political climate between Singapore and Malaysia has been historically tense, and a former Malaysian president once threatened to cut Singapore's water supply. These political pressures contribute motivation to establishing self-sufficient water supply within Singapore.

The recent watershed expansion with the Marina Barrage, as well as construction of desalination and reclamation plants have increased Singapore's supply capacity to at least 400 million m³/year, which is about half of current demand. The internal watershed currently provides 10-20% of supply. So Singapore must still expand its infrastructure to meet current demand. Even beyond that, historical growth in total water demand continues as observed in Figure 1-3, and if this trend continues the required expansion must be larger still.

Singapore's government is aware of the precarious nature of its limited internal natural re-

¹Singapore dollars, ~180 million USD

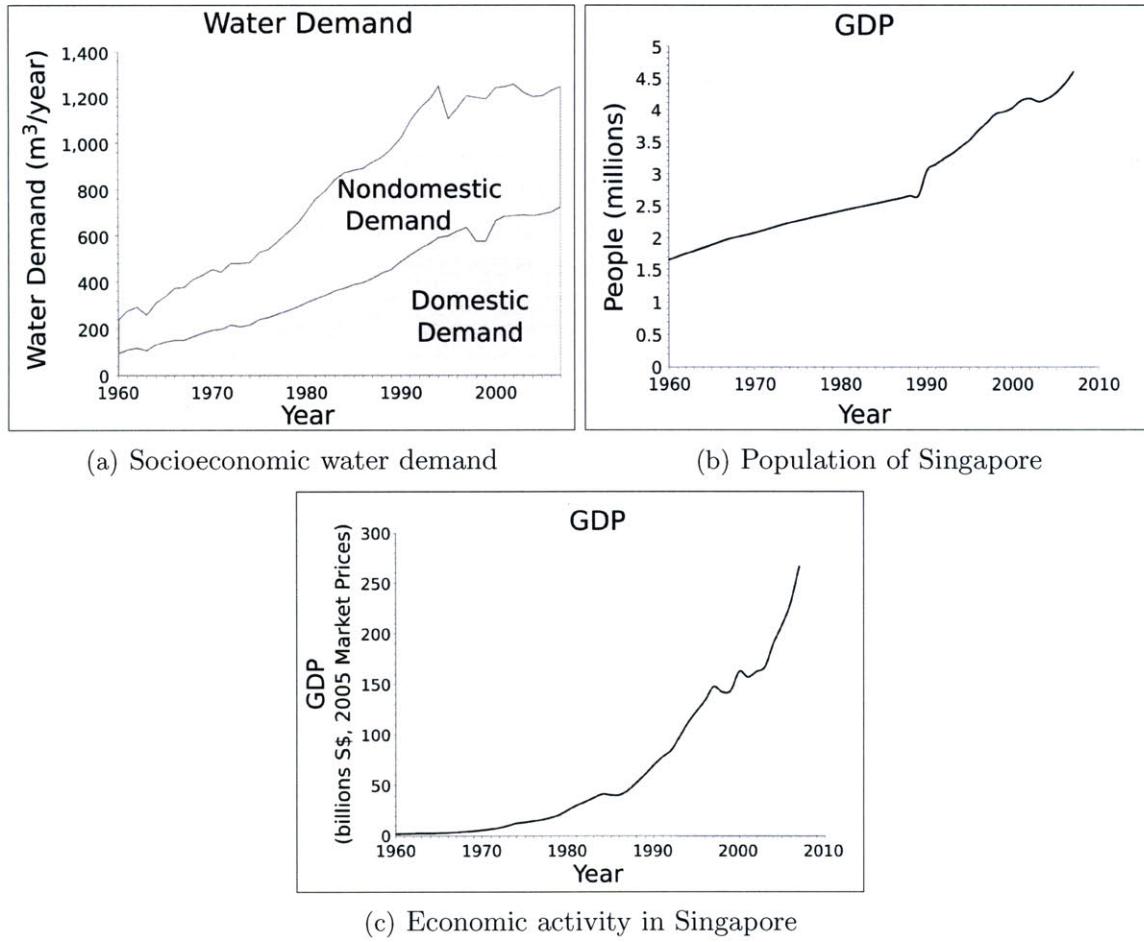


Figure 1-3: Growing socioeconomic activity and water demand in Singapore, graphed from PUB Annual Reports (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

sources and to counterbalance this threat Singapore has a long policy-horizon. This policy horizon is also achievable due to the low turnover rate of top government employees. The government is also strongly centralized and has a lot of control and leeway with pricing structures and funding. As early as the 1960s, even though the treaties with Malaysia were newly signed, Singapore began investing money and effort into identifying technological sources of water. Singapore has been an early adopter of desalination and reclamation technologies. With the maturation of these technologies, including the successful operation of demonstration facilities, Singapore commissioned large capacity desalination and reclamation technologies.

The capacity to invest in new technology depends in great part on its thoughtful pricing strategy[20]. The System Dynamics model would benefit from an inclusion of how invest-

ment in R and D led to new technologies. At the moment, the availability of new technology is considered exogenous. Now Singapore claims to be able to meet much of its water needs with capacity from desalination and reclamation such that if the Malaysian supply is cut off, they would be able to supply 100% of their water needs internally. If such a situation were to occur, the price of such technologically intense production would not bar them from achieving that.

Singapore is positioning itself not only as a leader in water resources but for sustainability policy as a whole. Although the island receives abundant rainfall (at 2.3m/year, the flux is twice the global average), there is limited area on which to store the water and evapotranspiration rates in the tropical climate may lead to losses of 50% or more. As early as the 1860s, less than 50 years after it was colonized by Great Britain, the first reservoir was built for urban water management. As a colony, the government of Singapore began to assess freshwater resources from the nearby mainland of Malaysia as early as the 1920s[20].

Water policies put pressure on limited resources that water infrastructure shares with other industries. For instance, in the past 50 years Singapore has reclaimed land from the coastline despite encroaching sea levels. At the same time this land expansion has been important for expansion of port trading area and urban development[36]. Still, the government has cited an interest in reducing material demands, while citing expansions to increase public transportation[20]. What is the overall impact of water resources on sustainability goals in other areas? In other words, what is Singapore's overall achievement in sustainability policy?

1.2.1 Problem Articulation

The disruptions caused by the early droughts motivated the young independent Singapore government to begin planning seriously for Singapore's water future. Over the course of the next 50 years, ambitious construction of water infrastructure allowed Singapore to continue to meet the increasing water demand that accompanied the rapid economic development and population growth and the economic transition from an industrial economy in the 1960s into

the early stages of a now service-dominated economy today[35]. This has been accomplished through careful financial planning and far-sighted demand projections[20] as well as by promoting conservation through education, water tariffing, and cost recovery.

The thesis proposes a model which examines the dynamic relationship between water consumption, affluence, and population for Singapore over time. The first goal for the model was that it reproduce endogenously the trends in urban water consumption over time. This required articulating feedbacks between resource availability and socioeconomic processes, especially those that lead to increasing demand. The second goal for the model was to articulate a dynamic framework to facilitate goal-oriented evaluation of material intensity indicators used in sustainability policy. The final goal for the model was that it be applicable to any urban system and provide a basis for comparison of water intensity and sustainability policy.

One of the main points of interest is whether the management policies identified by Singapore's policy makers contributed to the successful provision of water supply and to assess how well these management policies might perform under climate change and other stresses. These aggregated metrics are used to evaluate scenarios identified by city managers to be the targets of their policies, and the non-specificity of the type of infrastructure and technology facilitates the application of this model to other cities. The model formulation therefore includes variables that are important to decision makers as identified in the work by Tortajada[35] and Tan[20], such as water pricing strategies as well as time scales for making decisions.

System Dynamics was chosen as the modeling paradigm because of its capacity to handle feedback loops and non-linear relationships without large computational intensity. There is a precedent in applying System Dynamics with success and utility to business and management situations that lack data on social variables. The software is highly visible, which is an important feature when considering future impact in policy-making. The theory behind System Dynamics is based in controls and the mathematics is easily applied to physical processes involving flows, such as population dynamics or water use[37]. Many System Dynamics

models of water resources found in the literature focus on physical systems, without taking advantage of System Dynamic's methodology for estimating and approximating important social processes[38]. System dynamics has often been used to approach policy/management-related problems for complex systems. It has also been used to approach the problem of global sustainability and urban system processes with some success. More recently, System Dynamics is being used to examine environmental impact within the socioeconomic context of a city [39]. This type of study is very important in developing more holistic measures of sustainability and in using those indicators to manage our natural resources to best achieve our other societal goals.

The first step in problem articulation was to identify the main goals for Singapore's decision-makers with regards to water supply provision. Summarizing the historical behavior and decisions and decision-making processes described in *Water management in Singapore*[35] and *Clean, Green, and Blue*[20], three goals were identified as paramount to the water management approach of Singapore. First, the main goal of Singapore's water utilities is to provide a sufficient supply of water to meet demand². Second, since governments exist to provide increased social stability[41, 42], it seems a reasonable extension and distinction that this supply be stable³. Finally, since Singapore policy makers are promoting Singapore as a leader in sustainable planning and management[20], it was important to include the goal of overall environmental sustainability.

The three management goals identified by Singapore decision makers are:

1. To provide a water supply sufficient to meet demand
2. To manage the water supply in a way to increase its stability and resilience
3. To reduce the environmental impact of water provision

²As described by PUB, the mission of the water department is to be responsible for:
a. ensuring that there is an adequate water supply to meet the demand of consumers;
b. ensuring that the water that reaches the consumers is safe to drink[40].

³Resilience is a system property that is a measure of stability relative to system stresses[43].

The next step involves an articulation of the problem to be modeled within System Dynamics. With regards to Singapore's case specifically, the following statement was proposed to bound the experimental design:

Dynamic Hypothesis 1 Given Singapore's current water policies (the specific reduction targets and increased desalination and reclaiming capacity they have formulated), Singapore will be able to meet water demand in 2060 despite changes to water availability from Malaysia and climate change.

Some questions that arise with respect to the *Dynamic Hypothesis 1*, are:

1. How can we evaluate the claims Singapore has made with regards to its position as a sustainability success story and world leader in sustainable water policy?
2. Can Singapore's success be achieved elsewhere, even though in some ways it has operated under unique conditions?
3. What combination of factors and growth patterns might contribute to declining capacity?
4. What measures can be used to address declining capacity?
5. What are the material, energy, and financial resources required to provide existing capacity and expand in the future?

To benchmark the capacity of Singapore's water supply to meet the management goals identified above, the model must explicitly include system processes pertaining to those goals. The first system property modeled must be the water stock, whose value depends on the capacity to supply or produce water and the demand. Socioeconomic water demand depends on the magnitude of urban activities and the relative water intensity of each activity. The relative water intensity is a measure of the relative water efficiency of that activity. Domestic demand is related to household size and affluence and will be modeled endogenously. Non-domestic water intensity depends on the type of industry and technology and although the

Table 1.1: Table of metrics important to Singapore's water supply management strategy

System properties (stocks)	Main inflows and outflows	Types of inflows and outflow	Processes affecting inflows and outflows
Water resources (units: volume)	Water Supply	Natural inflow	Local watershed area
			Precipitation input (Volumetric height) Evapotranspiration Residence time (determined by topology and other factors) Water quality
	Man-made inflow	Technology Infrastructure Financial resources	
	Water Demand	Magnitude of urban activity Water intensity of urban activity	Size of economy Size of population Type of economy
Financial resources (units: dollars)	Revenue	Sales	Average affluence Demand
	Costs	Pricing Operation Maintenance Infrastructure Expansion	Affordability Policy and planning Size of infrastructure Complexity of technology Size of infrastructure Complexity of technology Size of infrastructure Complexity of technology

dynamic water intensity is modeled endogenously, the assumptions about the trends are considered exogenous. Singapore's approach to its utilities has historically been strategic with respect to planning and management of the financial viability of those utilities. Therefore a third system capacity modeled is the financial intensity of water (as an aggregate metric for energy and materials required per unit of water) relative to the utilities financial resources. The processes giving rise to a particular financial intensity are very much related on global economic trends, but the financial intensity is also related to the complexity of infrastructure, which is related to biogeophysical features endogenous to Singapore. These properties are summarized in Table 1.1.

1.2.2 The Modeling Process

The modeling process followed is summarized in Table 1.2. The first step in System Dynamics is to establish the dynamic hypothesis. This requires identifying the problem or goal to be modeled and an articulation of system processes and feedbacks that contribute to the outcome of that goal. The discussion in Section 1.2 was used in the formulation of the first dynamic hypothesis in Section 3.1. Since of the modeling goals is to create a model that is applicable to other cities, the situation in Singapore was considered in the context of sustainability, urban metabolism, and water management as considered in the second chapter. A more abstract dynamic hypothesis is stated in Section 3.1. The first dynamic hypothesis benefitted in particular from the paper by Tortajada, *Water Management in Singapore*, which attributes much of Singapore's success in creating a stable water supply in a water scarce area through careful financial planning[35]. The abstraction of this hypothesis for other cities benefitted from the paper by Milman and Short, *Incorporating resilience into sustainability indicators: An example for the urban water sector*, which created a questionnaire that created a city typology using an assessment of parameters contributing to the vulnerability of a water system's supply to external stressors[19].

Table 1.2: System Dynamics modeling process followed for thesis, (*from Business Dynamics*)[21].

Problem articulation and boundary selection	Theme Selection	What is the problem? Why is it a problem?
	Key variables	What are the key variables we must consider? What are the key concepts?
	Time horizon	How far in the future should we consider? How far back in the past lie the roots of the problem?
	Dynamic problem definition	What is the historical behavior of key variables? What might their behavior be in the future?
Formulation of the dynamic hypothesis	Initial hypothesis generation	What are the current theories of problematic behavior?
	Endogenous focus	What internal feedbacks might give rise to this behavior?
	Mapping	Diagram system and subsystem causal feedbacks Model boundary diagrams Subsystem diagrams Causal loop diagrams Stock and flow maps Policy structure diagrams Other facilitation tools
		Develop maps of a causal structure based on: Initial hypotheses Key variables Reference modes
	Specification	Structure rules Decision rules
Formulation of the simulation model	Estimation	Parameters
		Behavioral relationships Initial conditions
<hr/>		
Testing		
<hr/>		
Policy design and evaluation		
<hr/>		

The literature reviewed in the second chapter contributed to articulating the problem and in formulating the dynamic hypothesis, especially in a more generic way that adapted the problem articulation and dynamic hypothesis in Singapore to a more general case, which are the first and second steps of the System Dynamics modeling process summarized in Table 1.2. Surveying the literature on urban metabolism, integrated water resource management, sustainability, and modeling for policy assessment also contributed to the development of the more generic second dynamic hypothesis as well as establishing reference mode behavior and identifying the key variables for water systems in general. Surveying literature on resource consumption, climate change, and socioeconomic metabolism contributed an understanding of the context in which urban metabolism and sustainability intersect and some of the important concepts are collected here. Integrated resource models for water and cities contributed precedents for drawing system boundaries and the levels at which urban processes have been aggregated.

The causal loop diagrams and historical reference behavior that contribute to the formulation of the simulation model are presented in the third chapter. The third chapter also considers testing of some of the parameters for which less data were available and for non-linear relationships. The testing stage of the model required calibrating the model to endogenously recreate the trends in water consumption and provision for the growing city of Singapore from the time that its first reservoir was built in 1867 up to the present. This required calibrating the biogeophysical parameters that contribute to water supply and limit the expansion of water infrastructure, the responses of the domestic and nondomestic water intensities to changes in affluence and water availability, and the management mindset of PUB in expanding water infrastructure. The policy design and evaluation stage considered the response of current policy to changes in financial infrastructure costs to approximate the impact of losing access to Malaysian water (in an approximate way). A second scenario also examined how changes to climate, on top of financial changes, might alter the relative vulnerability of the water supply.

Since the long-term goal of this work is to develop a typology of cities based on water demand and supply management over time, processes specific to Singapore were aggregated and ab-

stracted in a way that would enable the methodology to apply to many cities, even cities with little data available. In particular, the methodology hoped to identify the relationships and feedback loops within Singapore that could replicate existing behavior so as to identify leverage points that might make the proposed water supply plan more robust.

The magnitude of water resources and the infrastructure which contributes to supply will be approached by metrics that aggregate these complex processes. Water resources are measured in units of volume and for this model all of the water resources are aggregated into a single stock. This means that all of the water in Singapore residing in lakes, groundwater, surface water, and pipes beneath the ground is treated the same way, instead of breaking the water resources into more specific stocks and processes that measure that volume. The approach to this is to assume that the infrastructure and biogeophysical characteristics of that infrastructure and the island contribute to an aggregated residence time. This approach of aggregating water stocks reduces some of the inertia inherent in a complex water system. Whether this is a reasonable or unreasonable approach can be evaluated and critiqued by water experts. Either way, the methodology of developing the aggregated water resources stock could in the future be assessed in close contact with municipal water experts.

Similarly, water production infrastructure is also considered in an aggregated way. This includes both the land that receives an precipitation influx as well as desalination and reclamation. In this way, water supply and demand processes can be compared with a unit that has a quantifiable physical meaning.

Data used in the model were obtained from annual reports published by the Public Utilities Board. The annual reports systematically report information pertaining to financial operation of PUB, including operating costs and sales volume. It would have been helpful to have detailed data on the production capacity of water infrastructure, storage volumes, storage volume area, total length and capacity of pipelines, and other information pertaining to infrastructure production, treatment, and storage capacity and residence times. This would have supported the more detailed breakdown and calibration of financial costs and

especially would have enabled a more explicit linking with material and energy demand. For the instances in which data was not available, the particular assumptions and approaches that were used to deal with this data and the gaps are described in the model formulations in the appendices. Many of the equations and variables were formatted based on work in the Second Water Utilities handbook[44, p. 8].

However, this model is intended to provide useful information about cities even when there is less data reporting than is ideal, as it is for many cities in the developing world. One of the next steps in this model is to develop a data methodology that describes the type of data sources that are necessary, how gaps in the data might be broached, and how to approximate data from interviews and assessments with experts on the water system.

Chapter 2

Developing the Dynamic Hypothesis

The dynamic nature of sustainability arises from feedbacks between carrying capacity, technology, affluence, and population growth. Defining goals requires imagining what sustainability might look like, and the dynamic nature of sustainability means that it will look different for different goals. What does sustainability mean for quality of life, if population is maximized at the expense of material affluence? What is a reasonable population size, if the goal is to bring everyone on earth up the the same level of material affluence? How should we value ecosystem diversity, national parks, or water quality? To answer these questions requires understanding the context of environmental goal-setting relative to the articulated socioeconomic goals.

Managing global resources requires the development of an articulation and agreement of social goals and an assessment of the natural resources required to meet them. The challenges in policy and decision making for sustainability arise from the challenges in both developing a common vision for society[45] and in understanding how society's metabolism of materials and impacts the environment. Developing successful policies for sustainability requires an understanding of how social and natural systems interact, and the complexity of social and natural systems and the difficulty in tracking feedbacks can create contradictory findings[46]. Societies are challenging enough to govern even without simultaneously attempting to govern the equally complex biogeophysical environment in which global society. In spite of this, progress in understanding these systems continues and many parallels exist between natural

and social systems[47, 48].

2.1 Society's Metabolism

Understand the relationship between resource consumption and socioeconomic processes that drive it is the domain of socioeconomic metabolism. A subset of this work investigates urban socioeconomic processes in particular. Three trends in resource consumption in particular require disaggregating relative to material requirements, since growth in all three areas is associated with material demand. First, a growing world population places increasing pressure on finite resources beyond what it would be otherwise. Second, average material affluence also increases resource demand even further beyond survival requirements of population. Third, even beyond the environmental impact of reducing available stores of materials, the social metabolism of one material may impact other materials or ecosystems that seem unrelated through the dense feedback networks that exist within natural processes.

Although cities drive the bulk of global material flows, cities are not inherently the agents of material consumption. For one thing, the figures reported above are those for bulk material flows, and do not give a full picture of how much of that growth can be attributed to economic processes the products of which may be transported out of the city. Studies have also found that cities benefit from scaling factors that increase the efficiency of providing some services such as transportation infrastructure [49, 50], and are therefore for some materials more efficient consumers of materials than society as a whole. Most importantly, cities are not and never have been closed systems, have always relied upon material inputs from their hinterlands to achieve the densifications of socioeconomic activities that characterize them.

The breakdown of quantities and kinds of materials consumed by cities changes over the lifetime of a city and levels of technology, and with these changes the relationship between the city and its hinterland changes also. For instance, food and other consumables have a short shelf life and the distance between the source of food and its point of consumption relies on

the capacity of transportation networks to bring the food to the consumer before it becomes inedible. Advances in and dissemination of food preservation technology, combined with the expansion of global transportation networks, can bring fresh fruit and vegetables from a farm in New Zealand to a table in England. Cities no longer rely on their local hinterlands for supplies, but can access any source from around the world. Changes in technology have increased society's demand for mineral resources like metals and decreased the demand for biomass materials like wood[9, 51, 52].

One suggestive way of examining natural resources from the perspective of natural systems is using the analogy of an organism[22, 23, 53]. These parallels are not only suggestive, but many authors argue that it is essential to examine natural and social systems interacting together, and that modeling one without the other cannot give a full picture of potential impacts or benefits, and particularly those in urban areas [52, 30].

“Socioecological systems are the primary unit of analysis, consisting of a structural coupling of a socioeconomic system with certain compartments or systems in the natural environment from which it draws upon for resources and which it modifies as a consequence, direct or indirect, of metabolism. The energy system represents the most basic constraint for the differentiation of socioecological systems, and therefore, systems that have in common a particular source of energy and the main technologies for its conversion will also share other basic characteristics, such as patterns and levels of resource use (metabolic profile), demographic and settlement patterns, patterns of use of human time and labor (time allocation profiles), institutional characteristics and communication patterns”.[9, p. 639]

Krausmann et al. document the major trends in material consumption over the past century from using the theory of sociometabolic regimes[9]. The premise of sociometabolic regimes is that world history, certain modes of human production and subsistence can be broadly distinguished that share, at whatever point in time and irrespective of biogeographical conditions, certain fundamental systemic characteristics derived from the way they utilize and thereby modify nature. The dynamic equilibrium for the agrarian regime is depicted in Figure 2-1.

Table 2.1: Yearly metabolic profile of the agrarian and industrial sociometabolic regimes.

<i>Parameter</i>	<i>Unit</i>	<i>Agrarian^a</i>	<i>Industrial^b</i>	<i>Factor</i>
Energy use (DEC) per capita	[GJ/cap/yr]	40-70	150-400	3-5
Material use (DMC) per capita	[t/cap/yr]	3-6	15-25	3-5
Population density	[cap/km ²]	<40	<400	3-10
Agricultural population	[%]	>80%	<10%	0.1
Energy use (DEC) per area	[GJ/ha/yr]	<30	<600	10-30
Material use (DMC) per area	[t/ha/yr]	<2	<50	10-30
Biomass (share of DEC)	[%]	>95%	10%-30%	0.1-0.3

Source: Reproduced from [9, Table 1].

^aTypical values for advanced European agrarian sociometabolic regime. In agrarian societies based on labor-intensive horticultural production with low significance of livestock, population density may be significantly higher, whereas per capita use of materials and energy is lower.

^bIn economies with high population densities, per capita values of DMC and DEC tend to be in the lower range, whereas per area values are high. In countries with low population densities, per area values can be very low.

A particular sociometabolic regime is one such set of operating conditions characterized by a particular type of dynamic equilibrium with the local environment. The regimes and their characteristics are summarized in Table 2.1¹.

The background section presented some of the main concepts of socioeconomic metabolism, including some of the main dynamic regimes through which societies have historically progressed. There are some concepts that are attributed to dynamic regimes of socioeconomic

¹A note on ecosystem equilibrium: ecosystem equilibrium is a concept related to ecosystem succession. For any particular ecosystem, there will be a set of behaviors at which it is considered to be operating in a "healthy" mode. Some ecosystems have more than one mode. This is said with the understanding that an ecosystem is generally in some kind of transition, or at least parts of it are at any given time. For instance, let's consider an old-growth forest. The trees are tall and very old, and tend to crowd out most other types of life. This is a type of dynamic equilibrium—for the most part, the trees will live with a set of other plants that have found niches living around the big trees. Sometimes a tree will fall down due to lightning, rotting, etc. This creates an opening which lets in more sunlight—it will be colonized first by primary colonizers that may grow in less than ideal conditions. Eventually other plants will take over and the set of plants and other organisms that characterize the ecosystem progress through several stages of ecological succession. The type of ecosystem characteristic to a region depends not only on the average climate and geology but also by how frequently disruptions occur. For instance some ecosystems even evolve to require frequent natural disruptions. There are some plants that require the occasionally fire for germination and others that may require periodic clearing by fires. Ultimately, it is difficult to meaningfully characterize any type or stage of ecosystem as being the "best". However, it can be said that there are certain ecosystems that are more likely under certain conditions. The dynamic equilibrium of ecosystems is akin to the dynamic equilibrium of sociometabolic regimes.

metabolism. These concepts are important for the development of the dynamic hypothesis for this thesis and also relate the theory of socioeconomic metabolism to other fields. For instance, biogeographical factors, including regional resource availability, contribute to formation of subtypes within regimes. Modern society is characterized best by the industrial regime, which is perhaps not a true sociometabolic regime. However, the importance of biogeophysical factors in regime formation is used in the dynamic hypothesis for this thesis. In particular, it affects both environmental model parameters as well as the financial intensity of water resource infrastructure[9].

Another concept that is assumed for socioeconomic systems is that when the system is operating within any particular regime, path dependency and resilience dominate dynamics and during transitions, discontinuity is assumed. Moreover, transition between regimes may be initiated when a critical set of conditions begins to transcend the possible range of dynamics of its current regime. In other words, for the most part the societal constructs are assumed to provide resilience to environmental changes as long as those changes are relatively small. Additionally, the idea of instability during sociometabolic transitions between regimes provides theoretical context for the stage in which global society is today. Also, there may exist subtypes of dynamic regimes that share biophysical characteristics but differ with respect to social structures, institutions, and culture[9].

The sociometabolic regimes proposed are hunter-gatherer, agrarian, and industrial whose properties are summarized in Table 2.2. However, it is important to note that the industrial regime should arguably be included, since it is not really a dynamic equilibria, because its reliance on exhaustible resources and overburdening of ecosystems further threatens long-term existence. The industrial regime of many developed countries is that of an advanced industrial regime.

During agricultural regimes, biophysical growth and population are strongly correlated and population is ultimately limited by the environmental carrying capacity. Land use efficiency might be increased by requires large labor inputs and ultimately is limited by labor supply.

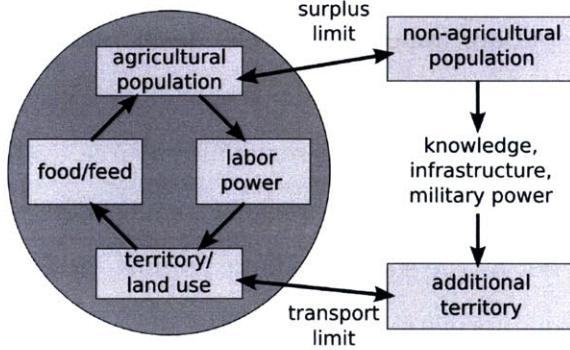


Figure 2-1: The dynamic equilibrium of the agrarian regime. An agricultural population invests labour to cultivate land and to produce different types of biomass (food, feed, fiber, fuel) sufficient to maintain a stable population. Under given climatic and soil conditions and cultivation technology, this may allow production of a surplus and provide a certain nonagricultural population and its activities with energy and raw materials. Growth of the agricultural population can be based either on territorial expansion or on increasing biomass output per unit of area. Intensification requires human or animal labor and is limited by diminishing marginal returns. The size of the nonagricultural subsystem is constrained not only by the surplus rate but also by the energy costs of transportation: Growth of the urban population can be sustained by an increase in the surplus rate—that is, by an increase in labor efficiency of the land use system in the hinterland (which is possible only within narrow limits) or access to a larger rural hinterland. Expanding the hinterland, however, increases transport distances, which ultimately constrains urban growth. (*Figure and caption reproduced from [9, Fig. 1]*)

Technological progress may increase the labor efficiency of population but ultimately will be limited by the biological productivity of the local hinterland. Therefore, within the agricultural regime, material and energy output per capita is strongly limited by biogeophysical characteristics.

In contrast, the process of industrialization fundamentally changes the relationship between cities, societies, and their local hinterland. For one thing, industrialization is characterized by the development of technologies that can capture the energy stored in materials with high-energy density as mechanical energy. This source of energy is not dynamically linked to the current biological productivity of the local hinterland and is also not limited to labor productivity. Instead, it can be used to increase labor efficiency. Moreover, the high-energy density enables the utilization of mineral resources. The early stages of industrialization are characterized by a continued need for human labor and a move of people and labor out of agriculture and into urban-industrial centers. As industrialization progresses, technology and

mechanization replaces labor, the material intensity of society increases, and as the demand for human labor decreases, population growth declines[9].

Many of these dynamics are captured within the causal loop diagram that is shown in Figure 2-9. Other dynamics that are related to industrialization are an outsourcing of labor, resource, and emission intensive processes to other areas. Technological advances increase the distances that can be reasonably traveled to obtain both perishable and non-perishable materials. The carrying capacities of industrialized cities are therefore no longer limited to the carrying capacities of their local hinterlands. Because of this, renewable local natural resources often rebounds and may effect a shift in mental model from a perception that natural resources are limited to a perception that resources are apparently limitless[54].

When the agricultural society began to reach the carrying capacity of its environment in a particular state of dynamic equilibrium (i.e. the limits of that particular socio-metabolic regime), then there certain socioeconomic processes that may be initiated that can increase the local carrying capacity of the system. However, these processes may not be sustainable in the long term. Exploitation of non-renewable resources is at the core of the industrial sociometabolic regime. Throughout the 19th and 20th centuries, the agricultural regime operated simultaneously with an agrarian regime. This was in part because industrial production increased demand for human and animal labor and population growth. The authors hypothesize that the movement towards a fossil fuel dominated energy system allowed a decoupling of industrial production and human labor and huge advances in intensifying the output of agriculture during the Green Revolution[9].

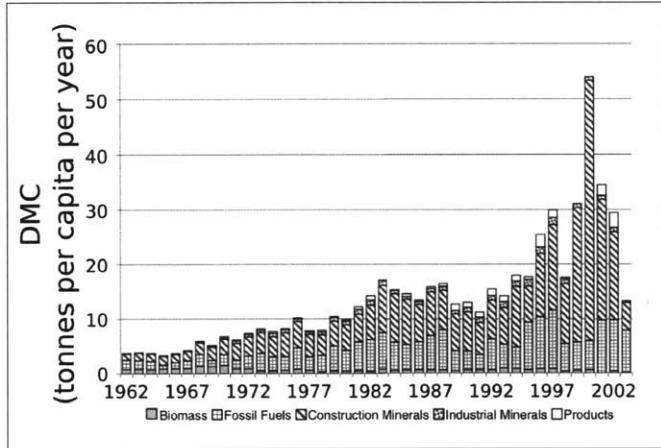
The relationship between the city and its hinterland have changed over time [22, 9]. Now that cities can access resources from far away, the local carrying capacity no longer limits the city to local resources. Land use change occurs in different stages and is relevant both in terms of the disruption of natural systems and for calculation of human impact. For instance, an urban area both offsets the ecological function that space might have otherwise (for instance, it changes runoff parameters) while also having consequences for environmental

impact (including increased water consumption and pollution). Land use change is driven by processes in the socioeconomic sector including the type of economy, population density, and affluence. Population and population density growth are identified as a contributing factor to deforestation, but "almost always operate in concert with political, economic, and ecological processes, and the relative impact of each factor varies depending on the scale of analysis" [54, p. 352]. Cultural factors such as changing contraceptive use and views on children alter family size and population density. However, that "changing the scale of analysis reveals examples in which population growth declined yet deforestation accelerated, population growth was accompanied by reforestation, or population growth attended a number of different human-environment responses" [54, p. 353] suggests that the impact of population on environmental impact is complicated to tease apart. These same trends have been observed in Singapore[10](see Figure 2-2).

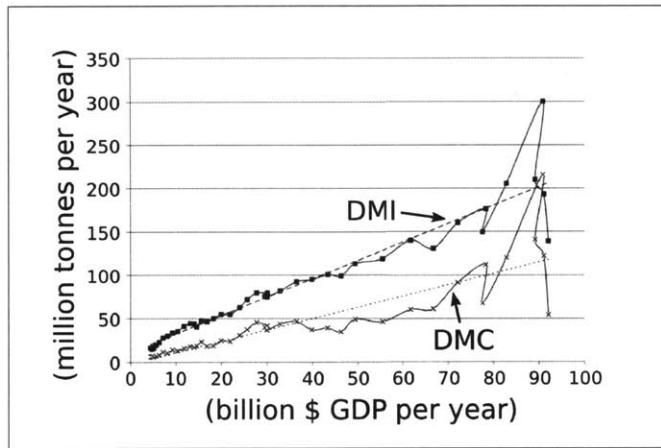
The idea of socioeconomic metabolism and transitions provides the theoretical support for hypothesizing functional units of drivers for the System Dynamics model that can be comparable within this framework. As observed in Figure 2-3, Singapore transitioned so quickly from an early agrarian regime in the early 1800s through a more advanced agrarian regime in the late 19th and early 20th that a dynamic equilibrium in the advanced agrarian regime may never have been reached. This quick transition was assisted by a transfer of technology from elsewhere in the British empire which made technology, knowledge, and resources more available to the developing island state. There is evidence that the local natural carrying capacity was exhausted by agricultural mismanagement by the end of the 19th century[11]. A collapse of biological productivity combined with the expansion of Singapore's trade network contributed to the reduction of agricultural land use observed at the dawn of the 20th as seen in Figure 2-3. It is likely that without the transition towards an industrial economy at that time that the local economy of Singapore would have faltered. This is an example of a society overcoming natural carrying capacity by transitioning into a different type of sociometabolic regime.

Table 2.2: Table summarizing characteristics of sociometabolic regimes[9]

Regime Type	Regime characteristics	Factors affecting sustainability of regime
Hunter Gatherer	<p>Has existed for more than 30,000 years</p> <p>Knowledge and technology limit capacity of people to modify local environment</p> <p>Lack of agriculture keeps energy quality and land productivity low</p> <p>Highly nomadic population with infrastructure and tools of relatively low material-intensity</p>	<p>Yield depends on ability to harvest and is highly dependent on labor</p> <p>Land productivity highly related to local characteristics and highly dependent on weather and chance</p> <p>Societies remain relatively small and dispersed without much social stratification</p> <p>Long-term structures limited by low energy surpluses and susceptibility to natural phenomena</p>
Agrarian	<p>Has existed for more than 10,000 years</p> <p>Fueled by a solar-based energy system (rely on energy conversion provided by biomass plants, which account for 95% of primary energy supply, with limited use of wind- and water-derived energy)</p> <p>Energy system directly linked to land availability and characteristics (a particular mix of energy types requires corresponding mix of land use, e.g. forest for heat fuel and cropland for food)</p> <p>Technologically-limited conversion efficiency of energy typically <5% place energetic constraints on development and growth:</p> <p>Labor input to fuel production requires food output be greater than energy input</p> <p>Carrying capacity determined by maximum primary energy produced per unit of land</p> <p>Agricultural society may generate a surplus such that it supports non-subsistence socioeconomic structures</p> <p>Limited exchange due to prohibitive energy costs of overland transport</p>	<p>Fertility of land</p> <p>Ability to maintain soil fertility</p> <p>Knowledge capacity to maintain soil fertility</p> <p>Availability of natural resources</p> <p>Balance between food supply and population growth</p> <p>Advanced agricultural land use systems in temperate climates could sustain long-term yields up to 30GJ of primary energy/hectare and support between 45-150 people/km²</p> <p>Management of soil, land and ecosystems</p>
Industrial	<p>Advancement in technology enables conversion of land-independent, energy-dense fuels into mechanical and chemical work</p> <p>Energy surpluses enable advances in metallurgy and other energy- and material- intensive technologies</p> <p>Advances in technology include advances in productivity of industrial and agricultural technology</p> <p>Soil fertility and other limits to natural carrying capacity can be supplemented by artificial means</p> <p>Fossil fuels spatially extend socioeconomic systems by enabling the use of energy-intensive transport</p> <p>Socioeconomic regime does not reach dynamic equilibrium with environment</p>	<p>Capacity to extract resources no longer limited by solar energy input</p> <p>Technology reduces labor requirements for production</p> <p>Enable a much higher local yield thereby enabling labor resources to enhance non-subsistence socioeconomic structures</p> <p>Natural carrying capacity raised, supporting higher population densities</p> <p>Local carrying capacity may be overcome by exploiting resources from other areas</p> <p>Stocks of exploitable resources limit growth</p>



(a) Domestic material consumption of Singapore [10, Fig. 3].



(b) Correlations between GDP, DMI and DMC in Singapore, 1962-2003 [10, Fig. 4].

Figure 2-2: The changing material requirements of Singapore's economy[10]. Total material requirements into the economy are measured by domestic material consumption in Figure 2-2(a) and have increased over time. This figure shows several spikes that correlate to years during which Singapore reclaimed coastline from the ocean[10, Fig. 3].

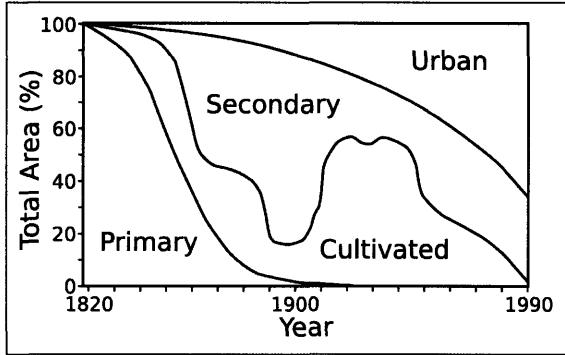


Figure 2-3: Graph showing land use in Singapore over time [11].

Urbanized land area, when considered relative to its impact on the water cycle, encompasses several land use types, between densely-built land and mid-density developments, including dense commercial, dense mixed-use residential and commercial, industrial, and mid-density residential. Güneralp and Seto[39] developed a System Dynamics model of how pollution has changed relative to changes in economic sectors for a rapidly urbanizing city in China, grouping economic activity into three sectors: primary (agriculture), secondary (material-intensive industry), and tertiary (service-based). The relative contributions to overall economic activity drive the overall use of land in urban areas. The past two centuries have seen Singapore transition rapidly from agriculture to less material intensive services, and the demand for land for industry has reduced relative to the size of the economy, as depicted in (see Figure 2-3). However, the burgeoning population and economy keep demand for land high. In Singapore, unlike many other cities around the world, the size of urbanized land area is rigidly limited by biogeophysical factors, chiefly, a coastline.

2.1.1 Carrying Capacity and Finite Resources

An import introduction to the modern study of population and resources is usually attributed to Thomas Malthus and his *Essay on the Principle of Population*, first published in 1798, wherein he postulated that population grows faster than resource (food) acquisition and thus resulting in a natural cap to population growth[54]. This, in its most abstract sense, is now commonly accepted population dynamics: there are a set of resources on which a

population depends, and if each individual consumes a given amount of resources, there is a natural cap to the population which is the quantity of the resource divided by resource consumption per individual, and this natural capacity is the carrying capacity of the system. Carrying capacity, in a nutshell, is the population that can be "carried" by a set of resources².

Over the past century, the notion of globally finite resources has been expressed with increasing frequency. One reason is that our consumption of resources is reaching the order of magnitude of flows of natural systems, as established with MFA³. The symptoms of this phenomena are that disruptions to healthy ecosystem functioning is being observed in all ecosystems around the world, including ecosystems far from the source of consumption. Scientists worry that by disrupting global flows of materials and energy, we are disrupting our ability to replenish our resources, and therefore threatening the carrying capacity of the natural environment. If we are depleting the natural carrying capacity, we put society at risk for undesirable dynamic modes such as overshoot and collapse and oscillation.

De Sherbinin[54] surveys the history of environment-population studies. Neo-Malthusianism is the term given to work that ascribes to the work of Malthus, whose work in 1798 stated that human population grows exponentially, while resources on which they depend increase more slowly, and therefore population will outstrip resources and result in either population or ecological collapse. "Neo-Malthusianism underpins the *Limits to Growth* model and implicitly or explicitly underlies many studies and frameworks" [54, p. 348], including IPAT[56]. It is a concept widely used by biologists and ecologists in modeling population dynamics to describe S-shaped growth. However, Neo-Malthusianism has been criticized for overlooking cultural adaptation, technological developments, trade, and institutional arrangements that have allowed human populations to grow beyond their resources base" [54, p. 348]. However, an alternative hypothesis by Boserup views technological progress and intensification of biological productivity as a process that occurs concurrent to population growth and will ultimately enable people to overcome natural environmental carrying capacity. These the-

²"An environment's carrying capacity is its maximum persistently supportable load (Catton 1996)"[55]

³Material Flow Analysis

oretical frameworks can and have been used as policy guides. While these theories differ in which process dominates population dynamics in a world with limited natural resources, they do not seem to be mutually exclusive and there is evidence to support both of these dynamic hypotheses. However, the difference can lead to different interpretations in the realm of policy: "In the case of neo-Malthusianism, population growth is the primary problem, and the solution is population programs. In the case of cornucopianism, market failures are the primary problem, and the solution is to fix them" [54, p. 350].

The notion of carrying capacity provides a basis for thinking about how population growth might vary. Any renewable resource can support a stable population that depends on the resource requirements of each individual in the population and also the rate at which the resource is replenished. The carrying capacity may change if the rate of replenishment of the renewable resource or if the resource requirements for each organism changes relative to the other. For instance, if a resource is consumed without being replenished, the environmental carrying capacity is depleted and the population may crash.

2.1.2 IPAT

"The IPAT equation makes us keenly aware of our limited choices" [13, p. 20].

The IPAT equation is a popular heuristic used in sustainability science for thinking about the impact of population on environmental carrying capacity. Chertow tells the story of the IPAT equation, beginning the article by presenting the equation in the context of its academic and environmental history and going on to discuss its various interpretations and transformations of its use. IPAT is simply an heuristic which identifies environmental impact as the product of three factors of population, affluence, and technology:

$$I = P * A * T \quad (2.1)$$

where I is environmental impact, P is population, A is affluence, and T is technology[13].

$A * T$ together represent a per capita environmental impact factor, F . IPAT is usually attributed to Paul Ehrlich, who, with John Holdren and Barry Commoner, published the formative papers on applying this extremely abstract equation in the early 1970s[13]. In 1972, Commoner proposed the an interpretation of the equation as $I = \text{Population} \times \text{Economic Good per Capita} \times \text{Pollutant per Economic Good}$, which reduces to $I = \text{Pollutant}$, a tautology. The equation is then a measure of “ ‘the environmental impact generated per unit of production (or consumption), which reflects the nature of the productive technology’ (Commoner 1972a, 346)”[13, p. 15]. Holdren and Ehrlich, 1974, disagreed with this interpretation, saying that by focusing on environmental impact as pollution “ ‘underestimated the role of diminishing returns, threshold effects, and synergisms, as well as the relation between ecosystem complexity and stability. They suggest that direct effects of environmental damage such as lead poisoning and air pollution are likely to be less threatening, ultimately, than the indirect effects on human welfare from interference with ecosystem structure and function...today better known as ecosystem services’(Daily 1997)”[13, p. 18].

Environmental Impact

The environmental impact term in the IPAT equation may represent more than one aspect of any resource under consideration. In this thesis, the environmental impact term will be interpreted as the water stock, which is the quantity of the resource available at any time. When a society is consuming close to all of the resources of a particular type in a biome it impacts ecosystem functioning, which has a feedback to society itself, as all societies depend on ecosystem functioning. The goal in sustainability studies is to identify patterns of development and manage or alter society’s metabolism in a way that allows us to maximize our resource extraction without undermining our ability as a species to survive while also enabling society to continue progressing artistically, technologically, and culturally.

Changes in environmental impact are driven by changes in the way society consumes resources. Exponential growth in population and economic activity have contributed to increased material demand, but material affluence has also risen. Critical for moving towards

greater sustainability in overall social metabolism is understanding how material consumption is related to socioeconomic processes such as increasing affluence and economic activity[51]. To provide context for modeling water demand over time it is useful to consider overall trends in socioeconomic metabolism and its changes over time, especially with regards to environmental impact.

An important aspect of understanding society's metabolism is linking the material inputs of society to specific socioeconomic processes. There are a number of methodologies that begin to link material flows to societal processes, and other methodologies that link material flows to environmental impact. Material Flow Analysis (MFA) is an accounting method that follows material flows from extraction to disposal and begins to link these flows to socioeconomic processes[57]. Environmental space is a concept that links material flows to a more intuitive interpretation of environmental impact and is known as environmental footprinting [58, 59, 60].

Spatial environmental indicators like water footprint and carbon footprint are metrics that suggestively link the idea of modern cities with international trade roots back to land-limited resources. The idea of a city and its hinterland inspired the concept of environmental footprinting. It converts a material demand into the area of land required to produce it. Environmental footprinting has been applied to a number of different resources, including water[60, 61, 62, 63], and can be an aggregated footprint such as the water footprint of a city or disaggregated by socioeconomic process, such as the water footprint of an apple or other product. Environmental footprinting is one of a number of methodologies that link environmental impact to space. For instance, Vörösmarty et al. use the idea of spatial environmental impact[64] to creating a spatial indicator for water stress.

The conceptual approach to MFA is summarized in the cartoon in Figure 2-4 and the assumptions and overall approach is described in Table 2.3. MFA was first developed as an attempt to bound traditional economics by relating economic processes to the thermodynamic concept of conservation of mass. Prior to this work the economy was conceived of as capable

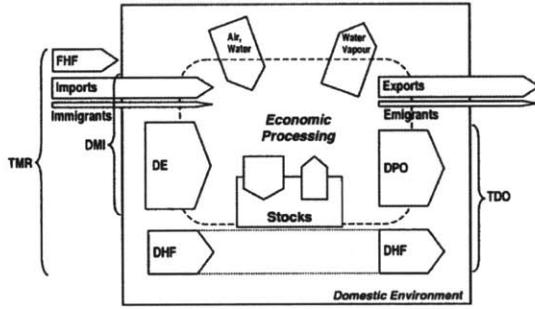


FIGURE 1. The metabolism of a socioeconomic system: The basic MFA model.

Source: Matthews et al., 2000; slightly modified.

$DE: \text{Domestic extraction}$
 $DMI: \text{Direct material input} = DE + \text{Imports}$
 $DHF: \text{Domestic hidden flows}$
 $FHF: \text{Foreign hidden flows}$
 $DPO: \text{Domestic processed output}$
 $TDO: \text{Total domestic output} = DPO + DHF$
 $TMR: \text{Total material requirement} = DMI + DHF + FHF$

Figure 2-4: Metabolism of a socioeconomic system[12, Fig. 1].

of boundless growth[12]. The goal of MFA is to increase economic growth by increasing the material efficiency of the economy[22, 23]. The idea that environmental impact need not grow proportionally to affluence is at the core of industrial ecology⁴.

Overall, although the material efficiency of economies is found to increase over time, material affluence has also been found to increase such that the overall per capita material consumption has increased over time[24]. Per capita material and energy use in industrialized regions are higher than developing regions by factors of 5-10[9], and most people in the world have consumption patterns somewhere between agrarian and industrialized. This data suggest that the transition from agrarian to industrial economies is currently an ongoing global process. Considering the increase in material demand that typically accompanies industrialization, total global material demands may grow by a factor of 2-3 in the coming decades[9]. The analysis shows that materials use has increased faster than population, but more slowly than the economy. The main trends in resource consumption profiles show that the physical economy has been transitioning from a throughput economy whereby the majority of physical flows are organic and have a residence time of less than a year to an accumulating economy whereby physical resources accumulate over time. Within each cluster of country types, the per capita use of natural resources differs, suggesting that the type of economy is not the only important driver in material consumption[9].

⁴Sources of theoretical concepts are summarized in several sources cited in the bibliography[58, 59, 65].

Table 2.3: Assumptions and conventions for defining system boundaries in MFA[22, 23]

Assumptions	<p>Conservation of mass</p> <p>Metabolism of socio-economic system is composed of the metabolisms of its compartments</p> <p>Includes the biophysical components of systems and subsystems, including complete metabolisms of human bodies, animal livestock, and artifacts</p> <p>Intra-system metabolism and exchanges are treated as internal transfers</p> <p>Artifacts are included as physical components</p> <p>Water, air, and other large volume physical byproducts are excluded</p>
Concepts	<p>Domestic Material Input (DMI) is a measure of the material requirements of socioeconomic activity in a country</p> <p>Domestic Material Output (DMO) and Domestic Processed Output (DPO) are a total of all materials produced in the domestic economy</p> <p>Total Material Requirement (TMR) is similar to DMC but also includes hidden flows (that are often on the same order of magnitude as direct flows)</p> <p>Domestic Material Consumption (DMC) is the difference between DMO and DMI, and represents domestic socioeconomic consumption</p>

Population

All other things being constant, population growth alone is enough to put pressure on finite resources. In Population and the Environment, de Sherbinin et al.[54] emphasize that it is unsatisfactory to attribute environmental change predominantly to population growth. Population is one of the more important drivers of socioeconomic consumption of materials. Each person consumes a certain amount of materials over the course of his or her lifetime. The more people there are, the more materials will be consumed. Given a set of finite stocks of resources required for survival, there will be a population carrying capacity that depends upon net per capita consumption. Also, population is a driver not only of a per capita consumption, but also of a societal consumption that exists beyond an individual's consumption and is related to the many socioeconomic processes that arise from society as a whole. Material consumption associated with an individual's personal consumption for survival and other

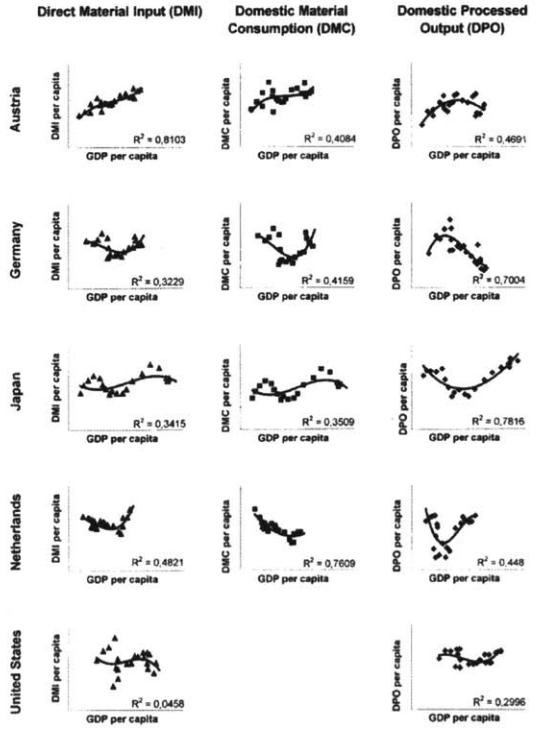


FIGURE 5. Environmental Impact and Affluence per capita Population I:
Environmental Kuznets Curves (EKC) for Material Inputs (DMI, DMC)
and Outflows (DPO) for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000; OECD; own calculation.

Figure 2-5: Environmental impact as an environmental Kuznets curve for several modern industrial economies[12, Fig. 5].

basic services may be considered the floor to consumption[66]. The floor to consumption is related to the society in which an individual lives, but there is also an absolute floor to survival, below which an individual cannot live[67].

Material Affluence and Quality of Life

”It is this third term in the equation that offers the greatest hope for a transition to sustainable development, and it is modifying this term that is the central tenet of industrial ecology (Graedel and Allenby 1995, p. 8)” [13, p. 22].

The product $P * A$, where A is defined as a per capita measure of wealth, consumption, or pro-

duction, represents an aggregate measure of total economic activity, such as total GDP. The idea of affluence seems more straightforward to measure and has often had a greater share of attention in the literature, leaving T as a “residual of accounting identity”[13]. Viewing T as a residual accounting identity generates an additional challenge to interpretation since macroeconomists do not agree on how to quantify in an absolute way economic growth and productivity in the economy[13]. Some of the discussion on environmental carrying capacity that used IPAT as a starting point focused on whether population or technology is a bigger contributor to environmental damage. ” ’The chicken-and-egg nature of this debate—whether population or technology is a bigger contributor to environmental damage—is revealing. Does an increased population call for improved technology, or does improved technology increase carrying capacity?’ (Boserup 1981; Kates 1997)”. Critique focused on the fact that the equation was not based on previous research: Deitz and Rosa, in 1997, ”the effects of population and economic growth on environmental degradation have not been extensively researched and are thus uncertain” [13, p. 18]. Meyer and Turner, 1992, criticized that neither affluence nor technology are ”associated with a substantial body of social science theory” [13, p. 19].

Both economic and material affluence are correlated with measures of overall quality of life[68]. This trend in increasing affluence may be reasonably interpreted as a drive to increase quality of life. In the thesis model, this will be formulated as an endogenous process relates increasing water demand with increasing affluence. However, material affluence is not the only condition necessary for a high quality of life. In fact, studies show that the *law of diminishing returns* seems to be active in this process, in that after a certain level of individual material comfort is established, a further increase in material comfort leads to marginal gains in quality of life. However, other social process that do increase quality of life, such as good health care, purpose in life and community, as well as art, the pursuit of knowledge and technology, are societal processes that may be associated with material demands outside of what is necessary for individual comfort. The ratio of material demands to societal benefits for these social processes remains poorly understood. Some societies provide these societal benefits more efficiently than others, suggesting that it is possible to some extent to reduce the material demands of quality of life in industrialized nations[68, 69].

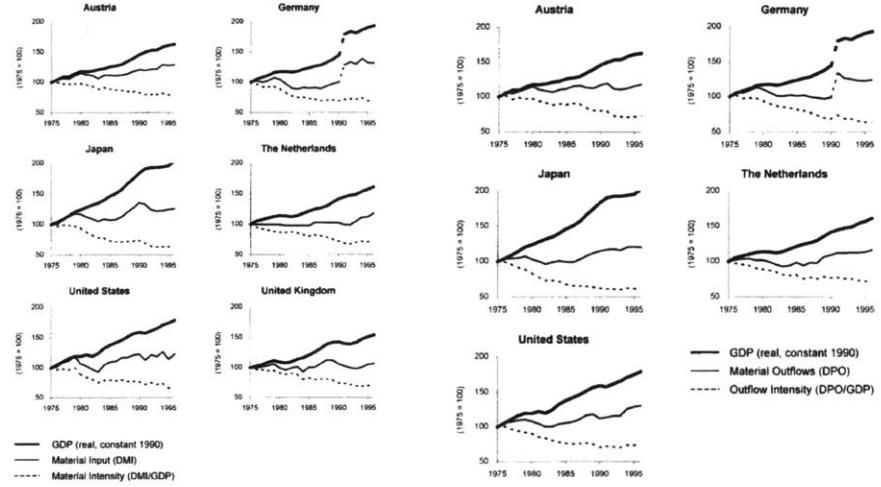


FIGURE 2. Environmental Impact and Affluence I: Material Input (DMI), Gross Domestic Product (GDP), and Material Intensity (DMI/GDP) for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000 (DMI-AUT, GER, J, NL); Adrianiene et al., 1997 (DMI-US); Schandl and Schulz, 2000 (DMI-UK); OECD (GDP); own calculation.

FIGURE 3. Environmental Impact and Affluence II: Material Outflows (DPO), Gross Domestic Product (GDP), and Outflow Intensity (DPO/GDP) for affluent industrial economies, 1975–1996.

Source: Mattheus et al., 2000 (DPO); OECD (GDP); own calculation.

- (a) Material inputs for several modern industrialized nations (b) Material outputs for several modern industrialized nations

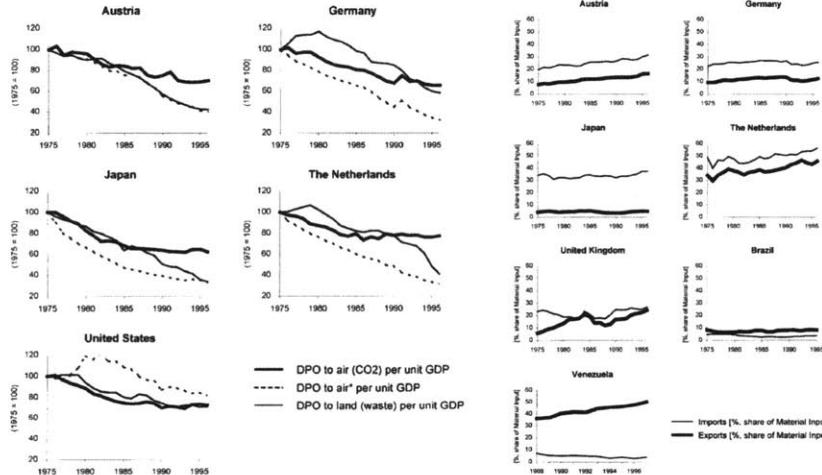


FIGURE 4. Environmental Impact and Affluence III: Outflow Intensity (DPO/GDP) by environmental media for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000 (DPO); OECD (GDP); own calculation.

- (c) Environmental impact for different environmental media (d) Imports vs. exports for affluent countries

Figure 2-6: Breakdown of material flows for several modern industrial economies[12, Fig. 2,3, 4, and 8]. That imports exceed exports suggests that the environmental impact of extraction has been externalized to other economies.

FIGURE 8. Material Profiles of International Trade: The relative weight of imports and exports of affluent industrial economies as compared to developing economies.

Source: Mattheus et al., 2000; Schandl and Schulz, 2000; Castellano, 2001 (preliminary data); Machado, 2001 (preliminary data); Authors of "The Weight of Nations," 2000 (personal communication); own calculation.

The dynamic hypothesis describing this increasing per capita consumption is that the desire to increase quality of life drives an increasing consumption in water demand. Surveys suggest that achieving a certain quality of life through material comfort is not associated with a reduced pressure to continue increasing quality of life[68]. In other words, the desire to increase quality of life seems to be driven by a reinforcing loop. Given the resources, therefore, resource consumption might increase indefinitely. Ultimately, however, growth in domestic consumption is checked by finite household financial resources or the availability of the resource itself.

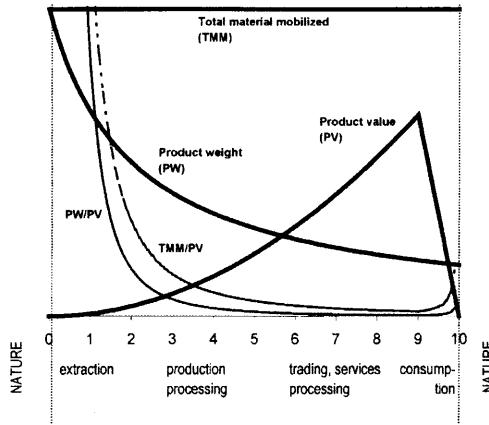


FIGURE 9. Model of extraction/production/consumption cycle in physical and economic units.

Figure 2-7: Diagram of production and consumption.

Affluent countries have been shown to reduce the material intensities of their economies over time[12]. Both the overall material intensity of the economy and the per capita material intensity of the economy (overall material intensity normalized by population) were found to have decreased. However, the overall material inputs to these economies were found to increase over the same periods[12, 24]. This suggests that while the efficiencies of the economy may be increasing, it is not increasing enough to offset the increase in material demand associated with overall increasing socioeconomic activity. In other words, there are two processes occurring with the socioeconomic system that affect overall demand: in the one hand, the economic intensity of water is decreasing, but overall socioeconomic demand is increasing.

Table 2.4: Table outlining how materials are tracked from extraction to disposal through the global economy in MFA[12]

Theoretical economic stage of analysis	Properties of economic stage
Resource lies in nature	Resource has maximum weight Zero economic value Indefinite material intensity
Next stage is resource extraction	Mass extracted is lower than that in nature, but not by too much Accrues economic value of usable parts Net economic value is proportional to the effort invested in extraction Relative economic value low High material intensity
Production	Mass entering production much lower than that leaving Mass efficiency is low Economic value increases Material intensity decreases during this stage
Consumption	Material intensity reaches minimum
Disposal	Material intensity may be indeterminate or negative

Fischer-Kowalski and Amman[12] suggest that the increasing material efficiency of socioeconomic metabolism could be driven by a technological change that is itself driven by an emphasis on cost reduction and profitability. Other processes that might drive increasing material efficiency are changes in consumption patterns that lead to decreasing material consumption per individual and changes in the international division of labor, characterized by the externalization of the most materially intensive processes of raw material extraction and industrial production. Studies suggest that technological change and externalization of environmental impact are the likeliest processes[12, 54].

However, traditional MFA does not directly support the linking of externalized environmental impact to the end consumer of a particular material good[12]. As outlined in Table 2.4 and depicted in Figure 2-7, an economy that depends more on processes closer towards extraction will be more materially intensive than a process later on in the manufacturing process. For

instance, traditional agricultural economies have a high material intensity since even a modest level of material comfort is characterized by a high material input with little economic value. In developing countries, material turnover would be greater than what is consumed by the local population for material comfort, and income from raw material exports would be used to prove the material intensive structures required to extract and produce raw materials; only a small fraction of national income would be left to import expensive and material less intensive commodities. The results of these studies suggest that the correlation between environmental impact and affluence is more complicated than that suggested by IPAT. Complexities arise from multiple areas, including scale of impact, boundaries, and the internal complications of accounting. Overall, however, MFA is widespread in evaluating socioeconomic environmental impact since it enables tracking material requirements through the socioeconomic system[12, 57].

Table 2.5: Summary of Trends in Sociometabolic Metabolism of Industrialized Economies[24, 12]

Increasing efficiency in economic activity (fewer materials required per unit dollar)
Increasing affluence (increasing economic activity per capita)
Increase in relative demand for minerals and a decrease in relative demand for biomass
Increase in residence time of the materials in the socioeconomic system and an associated increase of the stock of materials within the socioeconomic system

These trends in socioeconomic metabolism are summarized in Table 2.5 and the observed externalization of environmental impact for more affluent countries suggest that the pressure to protect the local environment increases as society becomes more affluent, and perhaps also as these industrialized countries exhaust their own local resources. The pressure to protect the local environment is not associated with reductions in overall material demands for industrialized societies. This behavior suggests that net environmental impact is just externalized to other countries who are willing to sacrifice environmental degradation for increasing affluence. Observations in support of this hypothesis include the documentation of affluent industrialized countries importing twice as much as they export (see Figure 2-6(d)),

the reverse for developing countries: exports exceed imports by a factor of 2-4 by weight[12]. Anecdotal evidence for externalization of impact also exists: co-temporaneously with the advent of Japanese policy preserving Japanese forests, Japan was observed to increase import of products from Indonesia with a subsequent decline of Indonesian forests[12]. DeSherbinin et al.[54] also notes anecdotal evidence of the exportation of environmental impact to developing countries. To summarize, there are four trends in socioeconomic metabolism of materials in industrialized economies are towards increasing affluence and associated per capita consumption of materials, an increasing overall efficiency of socioeconomic activity, and a change in the relative breakdown of the type of materials consumed (see Figure 2.5).

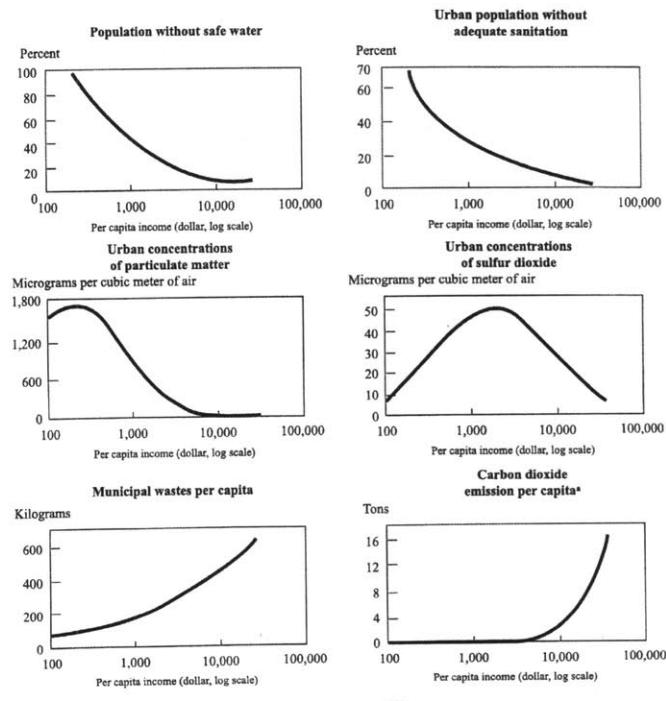


Figure 1 Relationship of affluence (per capita income) to various environmental impacts.
Sources: Hosier (1996) from Shafik and Bandyopadhyay, background paper; World Bank data.

Figure 2-8: Relationship of affluence to different environmental variables, Kuznets curves, [13, Fig. 1].

Environmental Kuznets curves have also been used to examine the factors that contribute to the nonlinearity of the correlation between affluence and environmental impact. Environmental Kuznets curves attempt to disaggregate the relative contribution of different factors

by graphing per capita environmental impact relative to other factors, such as per capita income (see Figure 2-8). These Kuznets curves depict the correlation between affluence and environmental impacts as third order polynomial functions, assuming constant population. Overall, socioeconomic metabolism at the national scale (measured as DMI, DMC, and DPO as depicted in Figure 2-4) was not found to be significantly correlated with affluence in a consistent way, as observed in Figure 2-8. This suggests that per capita income is not necessarily a distinct driving force for material consumption. This lack of distinct trend was also found true for CO₂ as well. Since CO₂ does not seem to be related to affluence, the authors suggest that per capita environmental impact is a function of typical production and consumption patterns in the national economy⁵. These results suggest that within any particular nation that there is a sociometabolic consumption that exists above and beyond that driven by individual behavior[66].

Technology

"In a provocative article, Rockefeller University researcher Jesse Ausubel asks: "Can technology spare the earth?" (Ausubel 1996a). It is a modern rendering of an epochal question concerning the relationship of humanity and nature, and, especially since Malthus and Darwin, of the effect of human population on resources. Surely, technology does not offer, on its own, the answer to environmental problems. Sustainability is inextricably linked with economic and social considerations that differ across cultures. This article, however, discusses the imperative of technological change and the role it can play in human and environmental improvement, particularly in the United States." [13, p. 14].

All other things being equal, the carrying capacity of global resources would be expected to diminish over time if individuals consume increasingly more. Yet population continues to grow. This suggests that the carrying capacity of initial resources was much greater than even what is available today or that the carrying capacity has also been growing. In the

⁵Note that as a fraction of domestic outputs, CO₂ emissions play a dominant role, making up four-fifths of outflows (see Figure 2-5). However, other material outputs such as wastewater were not included and would likely change the distribution of fractional outputs as they do for other metabolic studies[53, 51]

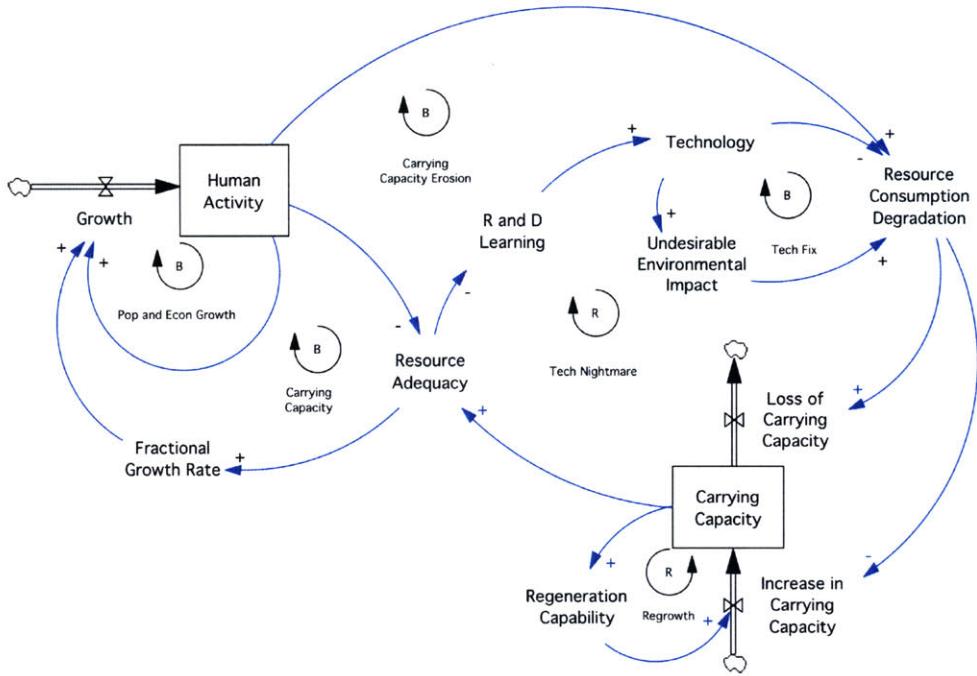


Figure 2-9: The role of technology is active in increasing the carrying capacity initially but is also active in a reinforcing loop with a delay that eventually increases environmental impact and potentially undermines carrying capacity in the long-term[14].

model developed for Singapore, technology is interpreted as knowledge or other infrastructure that extends the carrying capacity of some resource, either by increasing the quantity of the resource or by increasing the efficiency of its use.

IPAT, if interpreted as a mathematical relationship as stated, describes environmental impact as linearly proportional to the factors of population, affluence, and technology at various periods in time. This interpretation is contrary to research that shows that not only does the environmental impact change in a non-linear way with the three variables, but that its relationship varies depending on the resource and in some cases, the geographical region. However, IPAT has been interpreted that way even in practice where it is interpreted as (Holdren 2000): Energy use = Population x GDP/person x energy/GDP. The field of industrial ecology has used it as a master equation where Environmental impact = Population x GDP/person x Environmental Impact/unit of per capita GDP[13]. York et al. reformulated the equation to allow disaggregation of differences in influence and interactions between

population, affluence, and technology, and reformulate IPAT as STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology): $I = axP^bxA^cxA^dxe^6$ ⁶[70]. However, even if the linear relationship between affluence and technology and population is accepted as true at a particular instant in time, it is unlikely to be true at any other instant in time. Considering the many large uncertainties about feedbacks between variables, using IPAT as a mathematical relationship to evaluate environmental impact or carrying capacity at two different instances in time can only be so meaningful. Any attempt to apply IPAT to evaluate the trajectories of environmental impact or socioeconomic trends will tend to evaluate to misleading results.

Analyses of environmental impact and societal consumption that reference IPAT can help with goal-setting but should not be confused with a goal itself, since goals are value-based decisions. IPAT does not, as stated, assess environmental impact relative to social goals, and policies for sustainable development should make assumed social goals explicit in its identification of environmental benefits. Both affluence and technology are clearly linked to environmental impact[51], but ambiguities exist in the interpretation of affluence and technology for use in IPAT or STIRPAT. Affluence and technology are important socioeconomic processes, and the ambiguities that exist in their interpretation limit the application of IPAT to policymaking and decision-making. Given these limitations, however, IPAT has proved to be a useful heuristic for integrating different types of information about environmental impact and society, and its utility will improve as the methodology improves for its integration into more dynamic types of management tools and analyses for sustainable development.

2.1.3 Modeling Environmental Carrying Capacity

Although modern industrialized cities are no longer limited by the carrying capacity of their local hinterlands, the environment does still have a very real limit. Ultimately, people are biological organisms and are ultimately limited by the conversion of solar input to biological

⁶Where the variables a-d can be either parameters or complex functions estimated using standard statistical procedures, and e is the error term.

energy by other organisms. Therefore, although the local hinterland is not always a useful system boundary, socioeconomic processes can be viewed within the closed system of Earth and its natural resources.

Table 2.6: Variables from the Limits to Growth model[15]

Variable	Unit	Important Assumptions
Global Population	Number of People, Aggregate	Uses average birth and death parameters
Birth Rate	Crude, per capita	Endogenously calculated
Death Rate	Crude, per capita	Endogenously calculated
Services per Capita	Health, education, etc.	Higher levels raise life expectancy and lower birth rate
Food per capita	Kg of grain equivalent	Health goes up with availability of food
Industrial Output per Capita	Level of goods consumed	Measure of material wealth
Nonrenewable resources	Fraction of resource remaining	Renewed on time-scale long relative to 200 years Ultimate resource base Minerals and fuels aggregated into one variable One nonrenewable resource can be substituted for another
Persistent pollution	Volumes or concentrations	Arise from industrial or agricultural production Global distribution Persistence longer than decade Damage ecological processes

The *Limits to Growth* model examined the environmental impact of socioeconomic processes using this view of society within a closed global system. Table 2.6 summarizes the main variables in the *Limits to Growth* model. The *Limits to Growth* explored potential dynamic pathways for society's progress under different policy approaches to managing global natural resources. The modeling scenarios ultimately found that careful and specific management

policies were required to prevent oscillation of population or overshoot and collapse. “In 1972, a team of analysts from the Massachusetts Institute of Technology published *The Limits to Growth* (Meadows et al., 1972)” which model ”permitted Meadows et al. to examine the interactions of five subsystems of the global economic system, namely: population, food production, industrial production, pollution, and consumption of non-renewable natural resources. The time scale for the model began in the year 1900 and continues until 2100... Scientifically, it introduced Jay Forrester’s newly founded computational approach of ‘System Dynamics’ modelling and quantitative scenario analysis into the environmental discipline. By linking the world economy with the environment, it was the first integrated global model (Costanza et al, 2007). The salient message from the LtG modelling was that continued growth in the global economy would lead to planetary limits being exceeded sometime in the 21st century, most likely resulting in the collapse of the population and economic system, but also that collapse could be avoided with a combination of early changes in behaviour, policy, and technology”[15, p. 397].

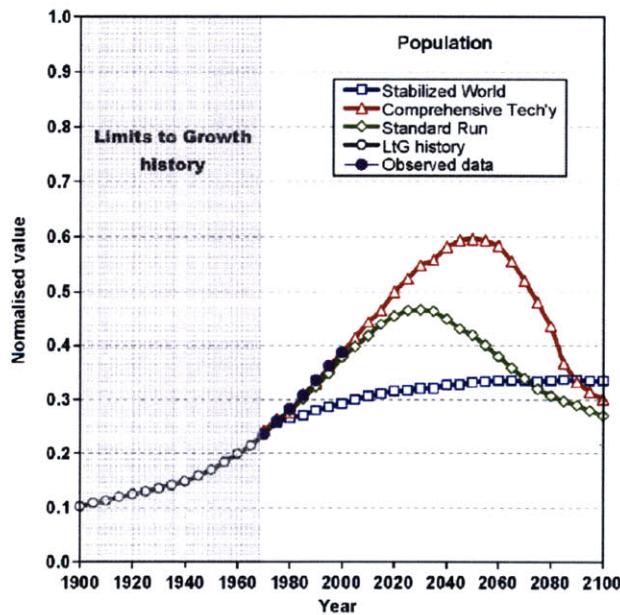


Figure 2-10: Limits to Growth scenario results for population[15].

Scenario runs from the Limits to Growth suggest that the most likely dynamic mode for world population is for overshoot and collapse, as seen in Figure 2-10. The ‘Stabilized World’ run

required careful balancing of input parameters, while the observed data follows the ‘Business as Usual’ or ‘Standard Run’ scenario[15]. Turner identifies four elements for understanding the constraints and behavior of the world system as summarized. First, the system behavior observed in the scenario runs shown in Figure 2-10 arises endogenously from assumptions about feedbacks within the subsystems that comprise the world system. Second, notice that in the short term, population dynamics are dominated by a positive feedback loop as illustrated by the exponential growth behavior. Third, the model assumptions include a feedback between population growth and stocks of natural resources that may be depleted, the growth is ultimately limited. Fourth, the presence of delays and inertia in the feedbacks between stocks of natural resources and population introduces instabilities into the long-term population dynamics. These instabilities reduce the predictability of the system response to corrective actions, which may have unforeseen consequences. The instabilities manifest as oscillation and overshoot and collapse dynamics in several of the runs[15].

Although the historic behavior currently follows the model trajectory, collapse may not necessarily occur where the model predicts. It could occur later...or sooner. Either way, the sensitivity of population dynamics to carrying capacity suggests that global natural resources be carefully monitored and managed. It suggests that current management methods are insufficient to maintain current trends in socioeconomic metabolism. The model also provides a platform for testing alternative management approaches.

While the results of the *Limits to Growth* are extremely thought-provoking and telling, the model was published to much controversy at the time, much as Jay Forrester’s *Urban Dynamics* had been in earlier years. Criticism at the time focused on the aggregation of many natural resources and processes and also on the fact that the results seemed to suggest or promote a global policy of population control[15]. That the historical data between the time it was first published and Turner’s reassessment suggest the relative soundness and usefulness of approximations made in the model. Additionally, the field of natural resource management and sustainability is no longer a fringe science and the field has produced a large variety of thought and method on identifying sustainable development policies.

Worldwater

Simonović developed the Worldwater model by adapting *The Limits to Growth* to focus on the dynamics of water resources[71]. The adapted causal loop diagram describing the main process modeled is shown in Figure 2-11. The scenario results showed similar dynamics to those produced in the *Limits to Growth*. The model considered a closed global hydrologic cycle and therefore all of the processes were considered to be endogenous to the system, which is described by the causal loop diagram in Figure 2-11.

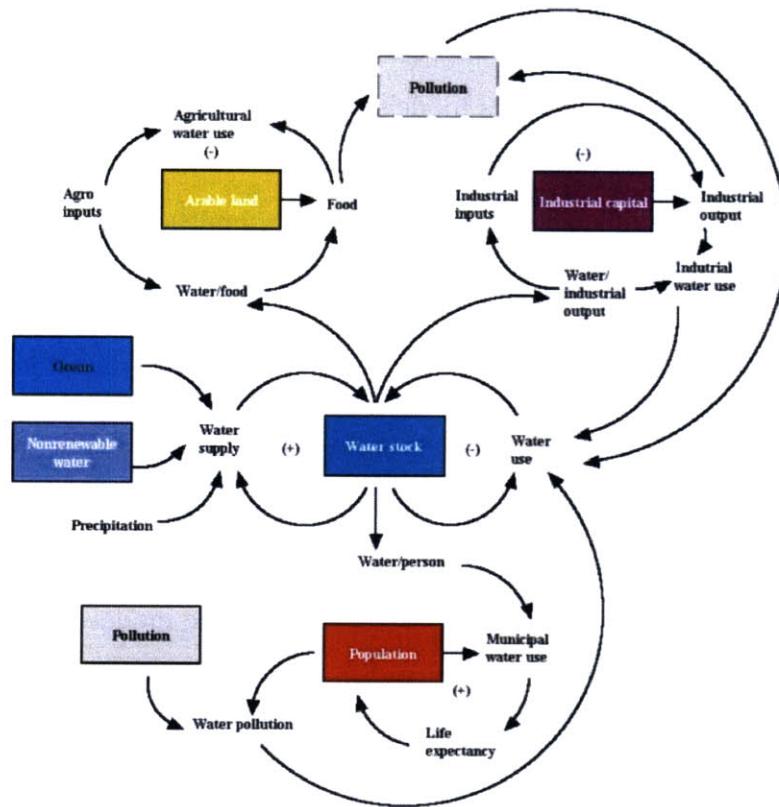


Figure 2. WorldWater model causal diagram.

Figure 2-11: Causal loop diagram describing the system boundary and main processes included within the Worldwater System Dynamics model[16].

However, for models like the *Limits to Growth* and *Worldwater* to be more useful to policy makers, they will have to be able to help policy makers assess scenarios that are at the same

scale as those on which policy makers make decisions. Although the issue is one of global resources and global population, for one thing decisions are not currently being made on such a wide international level and for another, decisions must still be made with respect to managing the processes that give rise to unsustainable resource use and to impact that occurs on regional and local scales. Models must be developed that can evaluate scenarios for scales salient to decisionmakers[17].

Simonović also emphasizes the importance of scaling down global models to regional ones, while noting the difficulty and challenges of doing so[16]. Other models include the investigation of the Las Vegas river basin[72] and the Zayandeh-Rud river basin in Iran [73]. The hydrological process in many of these regional models, like *Worldwater*, disaggregates water stock by their physical state and includes groundwater and surface water (as depicted in Figure 2-12(a)). These System Dynamics models of regional water systems tend to disaggregate socioeconomic demand and water quality to a greater extent than *Worldwater* does and also include more specific water policies such as those shown in the causal loop diagrams in Figure 2-12(b) and Figure 2-12(c). As such, they are designed to be more salient to regional policy makers.

Most System Dynamics models surveyed broke water resources into groundwater and surface water sources, such as that depicted in the causal loop diagram in Figure 2-12(a). Some of the models explicitly considered policy parameters within the model itself, such as that observed in Figure 2-12(b) and Figure 2-12(c). Most of the models also disaggregated water demand by the type of industry, as observed in the causal loop diagrams in Figure 2-12(b) and Figure 2-11.

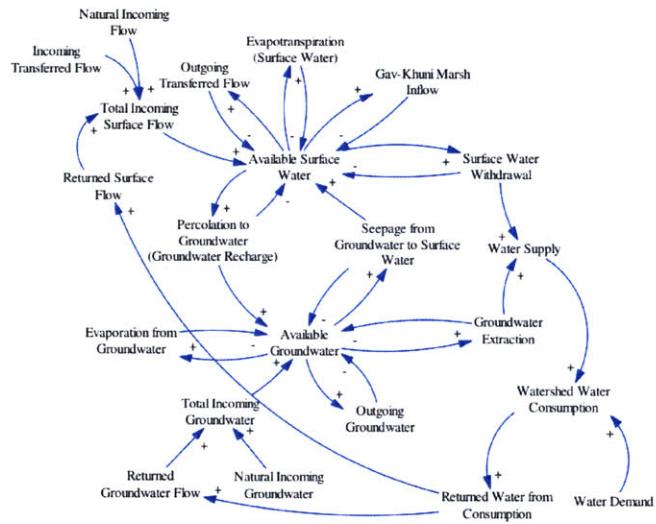


Fig. 2 CLD of the problem for the hydrologic subsystem

(a) Causal loop diagram for the hydrological cycle in one of the regional System Dynamics models[73].

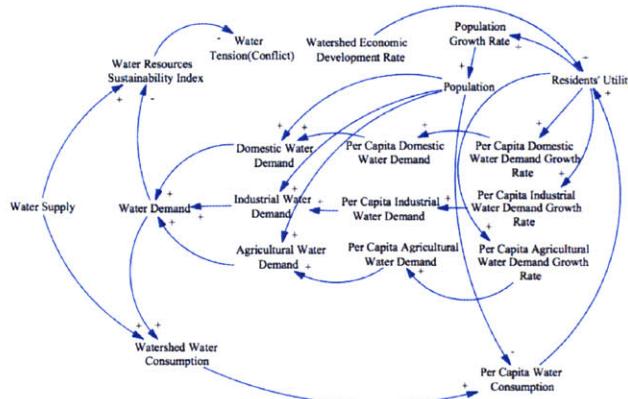
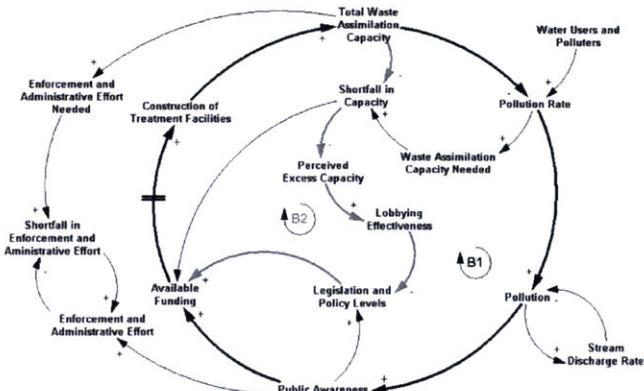


Fig. 3 CLD of the problem for the socio-political and economic subsystem

(b) Causal loop diagram describing the socioeconomic processes[73, 38].



(c) Causal loop diagram showing policy for urban water quality, [38, Fig. 1]

2.2 Supporting Decision-making for Sustainable Development

It was Tolstoy who opened one of his epic novels, *Anna Karenina*, by observing, “Happy families are all alike; every unhappy family is unhappy in its own way.” Tolstoy may have meant to imply that happy families *make it work*, and unhappy families do not, perhaps also have been offering his opinion that the ways in which families fail are perhaps more interesting and in some way varied than the ways in which families succeed⁷. Although perhaps not entirely applicable, this quote reminds me of systems and their dynamic modes of behavior (see Section A.1). If we consider ‘happy’ systems as those which approach equilibrium in a controlled, even-keeled, unsurprising approach and ‘unhappy’ systems as those which involve overshoot and collapse (with or without subsequent oscillation), we may observe that in the former, stable systems the internal parameters and dynamics have all been adjusted so that, regardless of external surprises, the internal dynamic synergizes in such a way as to continue progressing in as stable a manner as possible towards the system’s goal. In contrast, the ‘unhappy’ dynamic occurs when the carrying capacity of the system has been undermined, perhaps by the very processes that led to exponential growth, and is an important consideration in defining sustainability.

Unsustainable resource management and environmental degradation are global problems arising primarily from disperse sources[17]. Social systems are fundamentally vulnerable to changes, especially large changes in the environment. Governments and other social institutions seeking to provide stability for a growing population are increasingly motivated to understand the ways in which they are vulnerable and also the ways in which these vulnerabilities may be reduced both by amelioration of the problems and also by adaptation to change.

The interconnectedness of resources and policies presents a challenge to developing sustain-

⁷Tolstoy does not offer his opinion on whether one is harder than another; they are probably both hard in their own ways.

ability policies. Policies in one area may result in increased efficiency in that area, but export the impact to another area. For instance, promoting the exchange of electric vehicles for internal combustion engine vehicles may allow fossil fuels to be exchanged for something else. Ultimately, however, nothing is done to reduce the energy requirements of society and indeed, some of the manufacturing processes may be even more material intensive. Achieving sustainability therefore requires coordination between sectors on goals. However, many policy makers have neither the time nor the expertise to perform this kind of analysis, and even experts in sustainability in one field may find it difficult to predict what the impact in other fields might be. Models are therefore critical to facilitate exchange of ideas and issues from one field to another. One functional requirement identified for the model was to interface in the future with policies pertaining to other types of materials.

Table I Causes and impacts of major types of urban environmental issues

Type	Typical issues	Causes	Major impacts	Spatial extent of impacts
Type I: Poverty-related issues	Low access to safe water, lack of sanitation facilities, organic pollution of water bodies	Low infrastructure, rapid urbanization, income disparity	Sanitation-related health impacts, such as diarrhea and infections	Local
Type II: Rapid-growth-related issues	Air pollution (SO_x , particulate, etc.), water pollution (heavy metallic subjects, BOD, COD), industrial solid waste pollution, and so forth	Rapid industrialization, low rate of emission treatment, lack of effective management	Typical industrial pollution disaster, Minamata Disease, Onsan Disease; deterioration of regional ecosystem	Local and regional
Type III: Wealthy-lifestyle-related issues	CO_2 emission, NO_x concentration, municipal waste, dioxin, and so forth	High-consumption lifestyle, low local incentive for improvement	Global warming, chemical ingredient- and dioxin-caused abnormalities in infants, overextraction of resources, and so forth	Regional and global

Source: Bai and Imura (2000).

Note: BOD is biological oxygen demand; COD is chemical oxygen demand. SO_x = sulfur oxides; CO_2 = carbon dioxide; NO_x = nitrogen oxides.

Figure 2-13: Summary of environmental issues[17, Table 1].

One of the biggest challenges in the area of sustainability is that the temporal and spatial scales on which the problems that the sources of environmental pollutants are produced are not matched with the scales required for addressing them, as summarized in Figure 2-13. This mismatch of scales creates difficulty both in defining appropriate goals and action and

in monitoring. As an example, consider the role of greenhouse gases in global climate change. Many of these greenhouse gases, such as carbon dioxide and methane, are relatively non-toxic, odorless, and colorless gases that are natural byproducts of ecosystem processes. These gases have come to be identified as environmental pollutants because of their acceleration of global climate and the potentially undesirable consequences that might arise from large changes in global weather patterns. Unlike other environmental pollutants like CFCs or DDT, carbon dioxide is attributable to many processes that are difficult to legislate due to their variety and frequency. These gases leave the site of their production and enter unnoticed into the atmosphere. They are not easily attributable in space to the processes that produce them. Additionally, the potential impact of these pollutants are removed in time from the time of their initial production; much of the greenhouse gas now in the atmosphere was produced many years before.

Cities not only have an important role in the global economy but also occupy an important policy scale for sustainability. Cities have been identified as one of the most important scales at which environmental problems must be addressed[17, 74], and despite mismatches in temporal and spatial scales between environmental problems and urban policy making, cities around the world, including Singapore are emerging as leaders in sustainability policy[20]. Cities are hubs in the global economy, and nearly all resources pass through the urban environment[51]. They are the sites of important socioeconomic processes that transform material and energy, a process known as socioeconomic metabolism. Nevertheless, the city is no longer a concentration of people and things in a relatively local resource hinterland[51].

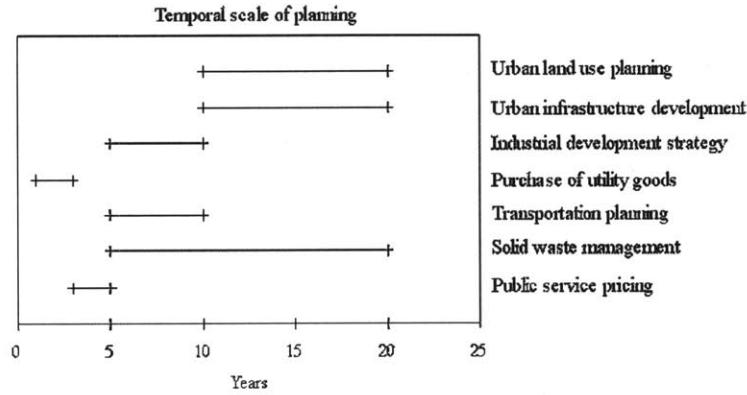
As hubs of population and economic activity, urban centers are critical players in global resource consumption and therefore sustainable development[27, 75]. Between 1900 and 2008, the percentage of the global population living in cities increased from 10% to 50%, and it is expected that over the next 50 years 95% of net population growth will occur in cities, and the majority of this growth in developing countries[76]. Although, this unprecedented population growth took place on 3% of global terrestrial surface, 78% of the growth in carbon emissions, 60% of the growth in residential water use, and 76% of growth in biomass

consumption can be attributed to cities [76]. Using the concept of environmental footprints, cities require resource inputs that require ten to a thousand times their land area to produce.

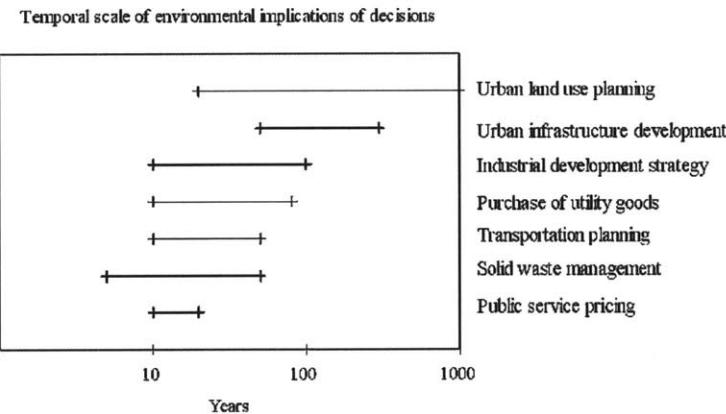
Cities are important both in terms of environmental impact and the scale of policy[17] and are important points of analysis for urban metabolism[77]. There are many factors contributing to a city's overall metabolism, include the climate of the city and what type of economy it has. The metabolism of a city in a tropical climate for a city on the equator will be different from a city at higher latitudes. But how different? How do they compare?

To facilitate the formulation of policy for fundamentally complicated and interdisciplinary issues, sustainability metrics have been proposed. However, since the material requirements of socioeconomic activity actually change over the lifetime and development of the city [78, 79], it is uncertain how meaningful existing metrics are for identifying sustainability policies for cities at different stages in development or relative to past or future scenarios. Moreover, the interconnectedness between processes makes the transfer of a policy successful in one city to another an inexact science. Understanding the dynamic complexity of material flow through cities, and the socioeconomic processes they support is becoming the object of study of metabolism in cities, and the relationship between cities and their hinterlands, is the area of interest for urban metabolism studies [51][52] [80].

Past work in developing a context for comparison of cities for the transfer of sustainability policy includes assessment of city size, shape and other parameters of its physical character; biogeographical parameters like climate, topography, and proximity to a body of water capable of transportation; and assessment of material flows. As an example of an assessment based on static parameters, Saldivar-Sali proposes an urban typology based on the water consumption profile relative to city demographics[81]. Other studies have looked into the importance of type of economic activities, city size and shape, location, climate and spatial distributions of activities for prediction material consumption[50].



(a)



(a) Temporal scale of urban decision making compared with temporal scales of environmental impacts[17, Fig. 2].

Scale domains	Driving forces		Emissions/sink changes			Radiative Forcing			Climate Change			Impacts			Responses					
	Popula-tion	Afflu-ence	Tech-nological change	Fossil fuels	Agricul-ture	Wastes	Defores-tation	Trace gases	Aero-sols	Reflec-tivity	Temper-ature	Precip-i-tation	Extrem-e events	Eco-sys-tems	Agri-culture	Coasts	Health	Mitiga-tion	Sequest-er-ation	Preven-tion
Global								■										■	■	■
Continental				■	■															
Sub-continental (economic/political/univer-sal)			■	■	■															
Large na-tions	■	■	■	■	■															
Small na-tions, states, provinces	■	■	■	■	■															
Large basins (5-10 grid-squares)				■	■															
1° grids				■	■															
Small basins				■	■															
Cities				■	■															
Firms				■	■															
Households				■	■															

(b) Spatial scale of the causes of climate change relative to the consequences[17, Fig. 1]

Figure 2-14: Figures showing the frequent mismatch between the temporal and spatial scales of issues pertinent to urban systems relative to the scales of urban policy-making.

2.2.1 Resilience, Vulnerability and Management

When you are confronted by any complex social system, such as an urban center or a hamster, with things about it that you're dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping. This realization is one of the sore discouragements of our century. You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn't counted on in other, remote parts. If you want to fix something you are first obliged to understand the whole system... Intervening is a way of causing trouble. Lewis Thomas[21, p. 8].

One inescapable challenge to both formulating sustainability goals and modeling them is that ultimately the motive for developing more sustainable methods lies in a desire to reduce the risk of a future in which we and our descendants are left with an unattractive future. The problem is that defining risk in a particular situation is inherently, in and of itself, a value-laden activity, and requires detail be given such as "risk relative to what" or "risk relative to whom". Then, deciding whether action is required, and what action, requires value-judgments be made about "what risk is too much?" and "what are the best of these alternate scenarios?" [41].

Identifying risk and vulnerability places a large burden on policy-makers to decide the values that are important to the stakeholders and interpret them as a definition of risk. This activity becomes extremely controversial if the benefits, risks, posed are unevenly distributed within society, or if they change suggest by a formal risk definition require large changes in the ways things are currently done. Policy makers are more likely to shy away from controversial topics if pushing forward with them requires putting their personal reputation on the line.

Another attribute that is considered to be an important goal for social systems is resilience, or stability in the face of disaster or crisis[43, 18, 32, 82]. An important metric of the resilience of a water system is the system capacity to acquire, manage, and distribute a water supply sufficient to meet demand, and especially the size of the buffer. Factors that affect

it are any factors that can cause changes to demand or supply, especially when the change does not affect both supply and demand equally (in other words, they change relative to each other).

An undermined carrying capacity may lead to overshoot and collapse or system oscillation[15]. This dynamic mode of oscillations is characteristic of unstable systems[21]. Figure 2-15 symbolically depicts a type of management that often leads to unstable water resource management. When a resource, like water, is an essential part of daily life but its provision is sufficiently available and stable that there is a comfortable supply and little disruption, people begin to take its availability for granted. It is seen as less deserving of financial resources and careful management, and instead these resources are often diverted to areas characterized by crisis. If sufficient resources are left such that the supply is carefully managed and maintained, then the dynamic may remain stable over time. However, if instead those resources are diverted away, then the resilience of the system to physical stressors may decrease. If the resilience dips low enough, a physical stress may impact the system's capacity to maintain a sufficient water availability. If this is the case, people begin to realize how much they require and value their water supply and are willing to throw more resources at fixing the problem, as many resources as it takes. However, once the problem seems to be fixed, they may again focus their attention on other things. Aichinger calls this the *hydroillogical* cycle since it has often been observed in water resources management and planning[18].

The hydroillogical cycle describes a situation with respect to water resources. However, the

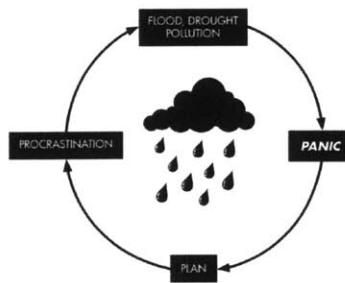


Figure 2-15: Hydroillogical Cycle from *The Water Environment of Cities*[18, Fig. 11.1, p. 231]. The hydroillogical cycle arises from a particular approach to resource management, typically involving delays and undermined carrying capacity, that prioritize 'firefighting' rather than preventative maintenance.

dynamic depicted in Figure 2-15 is observed in many areas; it is a common dynamic mode arising from a particular mental model from management, and is often called *firefighting*[21]. It is a particularly inefficient use of resources and recalls the old adage, “An ounce of prevention is worth a pound of cure”. Another example illustrating why the oscillation or overshoot and collapse of an unstable system are undesirable, consider the oscillation observed in the textbook case of population dynamics[83], perhaps an island with a population of wolves and a population of deer. If the wolves become very good at hunting, they may, especially on an island, eat so many deer that they are consuming deer faster than the deer can replenish themselves. If this is the case, the wolves may starve and die. Eventually the wolf population will drop low enough that the deer population may rebound, allowing the wolf population to increase. Both populations oscillate, and in both cases, the oscillation requires that periodically, processes that decrease population occur with a higher magnitude over a shorter duration than other times.

Table 2.7: Factors contributing to system complexity[21, p. 22]

Dynamic complexity arises because systems are:
Dynamic
Tightly coupled
Governed by feedback
Nonlinear
History-dependent
Self-organizing
Adaptive
Counterintuitive
Policy resistant
Characterized by trade offs

Despite the powers, variety, ingenuity, and adaptability of the human brain, nevertheless its computational procedures do have very real limitations. For instance, studies have found that people can only process several different types of visual information. In addition, people have been found to be poor learners when the process feedback is removed in time and space from the original action [21]. The more degrees of separation exist in time and space between an action and the reaction, the slower the learning process will be. The properties of systems

that contribute to dynamic complexity are summarized in Table 2.7.

One of the challenges in managing systems is that delays exist between the state of the system and the perception of that state. When there are a number of subsystems interacting together, the delays in feedbacks can give rise to system instabilities. It is important for water managers to know in what way their system will fail. In order to do this relative to water scarcity, a System Dynamics model was used to model the system and capture the main feedbacks operating.

Therefore, the types of goals that are set and how they are monitored can have a big impact on the success of those goals. Delays in feedbacks between where the position of the current state of the system relative to the system goal can lead to system instability[21] (and see Section A.1 for more information). Management of natural resources is no exception. With the wrong kind of policy, goals are never reached and societies collapse [84]. In 1968, Hardin described how not clearly laying out policies for use, or assuming that the system will optimize itself, can lead to collapse of natural resources in Tragedy of the Commons[85]. This type of behavior has been observed in real life quite recently with management of fisheries on the North Atlantic seaboard[86, 87].

Modeling has been found to be helpful in learning about large and complex systems⁸, and the management of natural resources involves many large and complex systems. There are many factors that contribute to the overall dynamic complexity of a system, some of which are summarized in Table 2.7, and both natural and social systems are characterized by processes that contribute to a complex system that is difficult to manage. Faced with the task of managing global natural resources, decision makers are increasingly using numerical simulation modeling approaches, such as System Dynamics, to inform policy and decision making[88, 89, 86]. Oreskes et al. note that "In recent years, there has been a dramatic increase in the use

⁸To use a mental model to design a new strategy or organization we must make inferences about the consequences of decision rules that have never been tried and for which we have no data. To do so requires intuitive solution of high-order nonlinear differential equations, a task far exceeding human cognitive capabilities for all but the simplest systems, even with complete knowledge of all structural relationships, parameters, and variables [21, p. 27].

of numerical simulation models in the earth sciences as a means to evaluate large-scale or complex physical processes. In some cases, the predictions generated by these models are considered as a basis for public policy decisions” [90, p. 641].

In addition to the challenges of managing a complex system relative to its goals, another challenge is formulating the goals in the first place. Policy and decision making for sustainability requires setting and evaluating value-based social goals⁹, and the task of articulating and agreeing upon social goals has its own set of challenges. Many social goals differ between cultures, which makes the identification of a common set of goals difficult. Moreover, achieving sustainability is practically related to reducing material consumption, which is closely related to quality of life. This raises issues of fairness since the majority of the world’s population lives below the poverty line and reducing material impact is simply not possible for these people[67, 34]. Guaranteeing a basic level of material comfort could therefore be articulated as a main social goal[67]¹⁰. This disparity can generate even more controversy in international goal-setting for sustainable development[30]. Although not always successful in overcoming such political and social obstacles, numerical modeling has a role in providing a quantitative platform for evaluating different types of policy scenarios in a somewhat unbiased way[42].

2.2.2 Challenges of Creating a Successful Model

Bringing numerical models into policy making and agenda setting adds another source of ambiguity in policy and decision-making. Both laypeople and experts often consider numerical models as objective analyses of processes. However, especially when the model involves evaluation of a social process, numerical models easily hide and skew value judgments[88]. For instance, consider a numerical model of the economic impact of a cap-and-trade carbon system. These numerical models translate carbon dioxide into a dollar cost and benefit,

⁹Value is related to the relative importance something seems in our lives. Maslow proposed a Hierarchy of Needs to illustrate the hierarchy with which various needs are given priority, with achieving basic survival being the highest.

¹⁰The fact that much of economic development and population growth is expected to occur in developing countries has not gone unnoticed[91] and raises important questions resource distribution, fairness, and values[66].

which can then be used to find a solution that minimizes cost and maximizes carbon reduction. Translating carbon dioxide into a dollar cost is a value judgment that prioritizes reducing the cost of modification to industry, and considers the cost of not reducing carbon impact to be zero. Furthermore, the optimum solution is defined as the value judgment that maximized carbon reduction and minimized cost[88].

It is important to understand that the use of numerical models in policy-making is never a purely objective task. However, when models are formulated rigorously and the value judgments taken and assumed are made explicit, numerical models can be very useful tools to assist policy-making[45].

The success of a model in informing decision making depends on more than the model's accuracy in recreating observed data. This survey of models used in policy making found that the models with the greatest impact with stakeholders and the most impact on eventual policy were models that had high degrees of saliency, credibility, and legitimacy. Unsuccessful models were usually weak in at least one of those three areas. Model validity is only one aspect of a model's credibility, which also depends on qualitative factors such as who sponsored and assessed the model. However, it was also found that models with high degrees of saliency, credibility, and legitimacy might also be unsuccessful[42].

Given that such complex models model large scale and complex physical processes, how can one know if claims of model validity are justified? Oreskes, et al. considers this problem with regards to the use of numerical modeling results in public policy decisions[90]. The authors conclude that the methods used for quantifying uncertainty often mislead model users *and* creators into thinking the model is more of a true representation of reality than perhaps it really is. The authors encourage modelers to use "a neutral language" [90, p. 643] when evaluating model performance, and to confine assessment of model validity to the performance of the model relative to observed data.

Chapter 3

Model Formulation

3.1 Water Supply Dynamics

Water scarcity arises when relative demand outstrips the supply. Any process that changes the value of demand relative to stresses the system in a way that might alter the capacity to supply for demand. Sometimes water scarcity is more visible than others. In the Atacama Desert, the driest place in the world, the soil is dry and sandy and the plants are small. In contrast, the water scarcity of Singapore does not seem obvious. Singapore is a small island country on the equator and receives an average of 2.3m of rainfall a year, which is twice the global average[35]. However, due to the high water demand arising from a large population and economy, Singapore is listed as one of the most water scarce countries in the world[20].

A water scarcity is in the end a quantitative scarcity, but it may arise from qualitative shortfalls. Although there may be enough water, there may be a qualitative scarcity if this water is contaminated by a toxic substance or infectious disease, in which case this qualitative scarcity becomes a very real quantitative scarcity of potable water. Such scarcities arising from qualitative concerns often arise in disaster areas where water infrastructure, especially basic sanitation and health services, has been disrupted. In such cases the water is poses an extreme health risk and is not fit for human consumption. Qualitative concerns also play a role in less dire circumstances. For instance, the aesthetics of water play a role in people's perceptions of what is potable[67, 34]. There are cases where even if water supply is suffi-

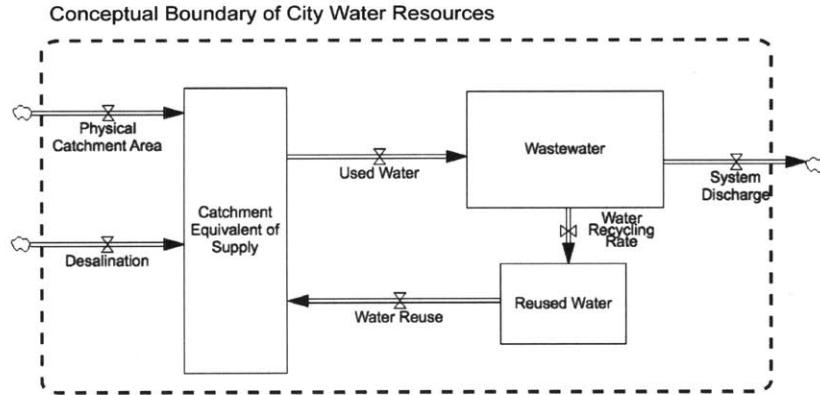


Figure 3-1: System Boundary of Water Flow System: The system boundary starts at the point of capture and ends at the point of disposal. In this way, the total water footprint and reused water can be examined more closely.

cient to meet demand quantitatively, aesthetic concerns such as taste and smell may prevent people from drinking the water. In such cases, people have even been known to consume from other sources that pose a higher health risk due to contamination from fecal matter and pesticides. Water quality also has economic repercussions depending on the economic application of the water.

The factors affecting qualitative scarcity are factors that pertain to the provision and treatment of water for potability. These include processes leading to contamination events, breakdown of water treatment, and point contamination. In addition to infrastructure actually deteriorating, the qualitative scarcity might arise from a lag between the standards for water quality, the policy protecting water quality, and the technology installed to achieve these standards and enforce the policy.

The cartoon in Figure 3-1 is a graphical representation of the range of processes that affect urban water supply. Decision making about water supplies occurs at many scales, and considering the decision-making scales and the scales of physical processes yields many potential system boundaries. Topographically, water resources of any kind draw from water inflow from a larger land area, so a political entity making decisions about their water source may need to interact with other governments within that region. Therefore catchment area is a useful designation for system scale. However, many cities draw from sources with inflows

from more than one watershed, or have manipulated local resources to transfer water from one watershed to another. So the watershed scale might not be entirely clear. Scales of social systems and processes suggest physical boundaries that may not match the physical boundaries suggested by physical processes. For instance, political systems may span municipalities. Water systems defined by social systems pose an interesting and important challenge to water system analysis. On the one hand, the central coordination of water planning and management that is often associated with a political body is an important policy approach.

In addition to the capacity to assess the validity of *Dynamic Hypothesis 1* described in Section, it is also desired that the model be applicable to other cities. After considering the literature, a second hypothesis was proposed to describe the dynamic behavior of Singapore and other urban water systems.

Problem Hypothesis 1.2 As a city grows, so does its demand for water. After locally available, more easily extractable sources of water have been leveraged, in order to continue increasing water supplies, increasingly complex, resource intensive, and expensive sources will be tapped. In other words, the material intensity per unit service (in this case water production, or increased water capacity) will increase as resources become progressively harder to extract. Extraction requires infrastructure, which may be funded by government, utility, or the private sector. In cases of extreme water stress, infrastructure may be informal, since then water has a greater value than it would otherwise. Because of the financial intensity of infrastructure, the capacity of government, or the city, to pay for infrastructure can ultimately limit the maximum socioeconomic consumption of water. Governments can to some extent reduce socioeconomic consumption beyond what it would be otherwise through conservation efforts, but as long as population and economy grow, so will water demand and the need for water supplies.

3.2 Bounding the Model

The model should capture whether the system, at some time, has the capacity to acquire, manage, and distribute a supply sufficient to meet demand. Any process that alters supply or demand relative to each other may alter the capacity of a water system to supply water and therefore water availability. The water supply depends strongly on natural cycles and the biogeophysical factors pertaining thereto, including climate, topography and geology, but is also affected by any societal processing altering biogeophysical system characteristics.

Table 3.1: Processes with inertia that affect system resilience

Water demand
Water infrastructure
Water resource
Land
Policy-making
Financial resources

Demand for water is also driven by both ecological and social metabolism[34]. Significant feedbacks exist between ecological and societal water demand. Changes in the built environment stemming from changes in sociometabolism may reduce the health and vitality of local ecosystems and reduce evapotranspiration requirements. Reduction in ecosystem health and diversity reduces their capacity to clean which, when considered relative to the operating requirements of treatment technologies, may alter society's capacity to clean and ultimately the system's overall capacity to supply. Ultimately, water supply and demand depends on many diverse, complicated, and transient processes. Whether a process should be included in the model depends on whether it fits within the temporal and spatial bounds of analysis.

Changing or unusual climate patterns can result in scarcity when habits that were born out of certain conditions stress resources under different operating conditions. Individual behavior and society's water infrastructure has inertia and cannot change instantaneously, such that sudden changes in parameters affecting relative water supply or demand may give rise to unexpected and undesirable system behavior. Milman and Short[19] consider the vulnera-

bility of urban water systems to acute or chronic changes that would affect the relationship of supply to demand and their approach is the starting point for describing the important feedbacks between supply, demand, and capacity to supply relative to demand for the urban water system.

Based on the reference behavior of socioeconomic activity, water demand, and water infrastructure, the causal loop diagram in Figure 3-2 is proposed as summarizing the main feedbacks between the socioeconomic system and water resources.

Stocks characterize the state of the system and provide the basis for actions:

- Stocks provide systems with inertia and memory
- Stocks are the source of delays
- Stocks decouple rates of flow and create disequilibrium dynamics
- Stock and flow structures should be included when they represent physical processes, delays, or stocks whose behavior is important in the dynamic you seek to explain

Water resources possess system inertia; they cannot be instantaneously depleted or expanded. The water resources depend on a physical infrastructure that collects, processes, stores, and distributes water to the socioeconomic system. This physical infrastructure itself has inertia is also modeled as a stock in this model. Additionally, both water infrastructure and water resources are require land resources. Land is limited resource on Singapore and several socioeconomic processes compete for land use as described in Section 2.1. Land resources are another system stock. Also, policy making is another structure that exhibits inertia. Decisions and planning take time to formulate and execute and are based on mental models that take time to be updated; there are several stocks that are modeled that represent the inertia in mental models of management. Finally, water infrastructure depends very much on the financial resources available to the government at any time. Similar to water resources, there is an inertia involved in collecting and spending this resource.

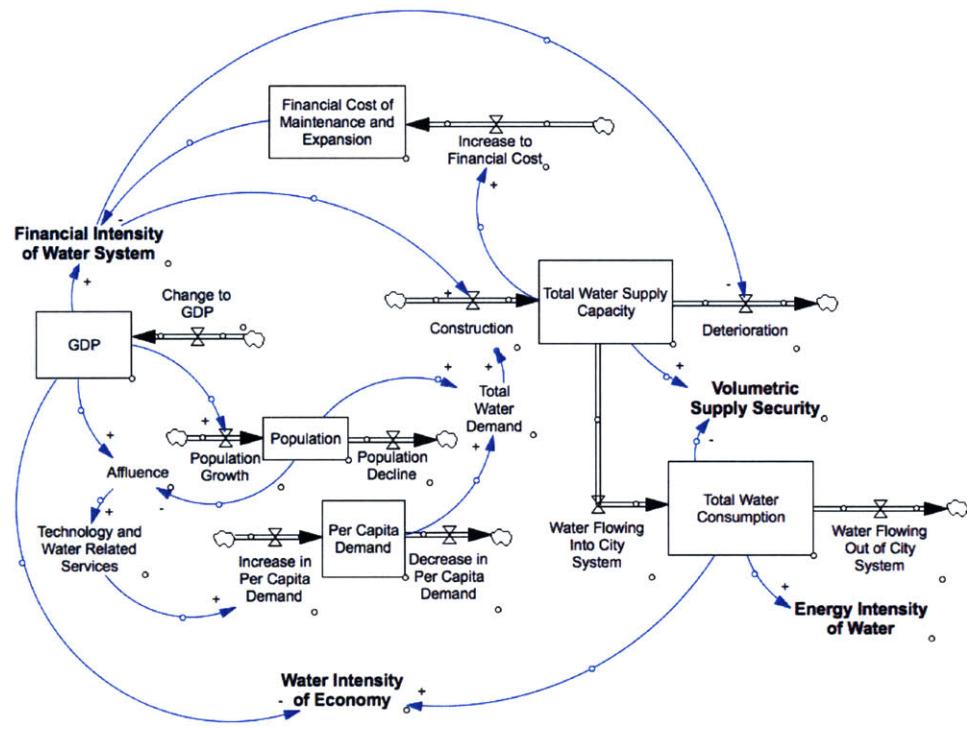


Figure 3-2: Important stocks and flows of Singapore's water system, disaggregated.

Demand for water depends on what it is used for and these requirements do not change instantaneously, as they are related to physical processes with stocks. For instance, water is required for living, and since the population does not change instantaneously, so at any given time the population have a demand for water that depends on population size and the per capita demands of living. The per capita consumption will depend in part on the affluence of people. Although affluence is not a direct consumer of water per se, the more affluent a person is, the more disposable income they have. The more disposable income they have, the more services above survival they have in their homes. The more services they have, the more services will require water relative to what they would have otherwise. Additionally, the economic capital at any time has a physical component: physical infrastructure associated with the type of industries in the economy as well as the technologies that they require. This physical capital cannot be changed overnight.

3.2.1 Bounding the System

The Urban Policy Scale

Table 3.2: Ways in which a catchment area may be defined

Topographically
By Collection Infrastructure
Jurisdictionally
By Production Capacity

With governments and other social entities often leading the way in commissioning studies for use in decision-making, the social delineations of water systems deserve thoughtful consideration in drawing system boundaries for sustainability planning and the creating of the models that inform it. It will become important not only for governments to coordinate with each other on shared water resources, but they will have to learn to integrate water planning with other types of planning, too. Urban policy affects many processes that important role in determining the quantity and quality of natural water resources[48, 32]. Some approaches used to bound water system studies are summarized in Table 3.2.

For urban policy scale it is important to consider the scales of demand and the scales of supply provision, as well as the processes that occur on scales that affect the capacity to supply. Figure 3-3 and No process outside of the most important scales will be modeled as stocks and flows. Water provides many intuitive ways for bounding a system of study at a variety of scales. One may be interested in considering how water flows through areas of a particular biome, or a particular topography. Topographical changes in the environment lead to natural delineations of watersheds at a variety of scales. Geological and topographical features together also lead to interesting systems such as fossil aquifers. Physical delineations based on social systems create another important typology of water systems. Legal and political systems may even create differing subsystems from each other. Water systems defined by social systems pose an interesting and important challenge to water system analysis. On the one hand, the central coordination of water planning and management that is often associated with a political body is an important policy approach. However, as the limits of regional

Table 3.3: Summary of potential policy levers (*adapted from discussion in Milman and Short[19]*)

Policy Goal	Potential Levers	Policy	Design Parameters	Variables
Altering natural supply	Changing quantity, time distribution, and quality of precipitation entering socioeconomic water system	Land use patterns and development	Encouraging adoption of rainwater harvesting Technology that changes collection	Runoff rates (infiltration rate, slope) Concentration and direction of runoff into socioeconomic system Pumping groundwater Fog collection Building of dams and other storage reservoirs Altering permeability of reservoirs and canals Altering evapotranspiration parameters
Artificial Supply	Increasing technological production	Type of water source (saline, wastewater)		
Managing Demand	Setting caps to demand	Determining acceptable levels for caps	Affluence	
Pricing strategies				

freshwater resources begin to be met, social institutions must coordinate their water policies with others who share access to water within the same physical system. Historically, these efforts can be an opportunity for cooperation[32].

The Spatial Scales of Water Supply and Demand

The spatial scales of water supply and demand cover eleven orders of magnitude or more, spanning evapotranspiration in plants (which occurs on the order of millimeters) to the global hydrological cycle (which acts over distances on the order of tens of thousands of kilometers). Such a large range would not be useful to policy makers and the propagation of uncertainty between scales would make the model unwieldy to use and create. In the earlier discussion,

Table 3.4: Important dynamic processes within the system boundary

Temporal Processes	Spatial Processes
Droughts and other changes in the timing, intensity, and duration of precipitation	Variations in ecotone, including vegetation type
Infrastructure construction and decay	Physical stock of infrastructure
New water policies/water use policies	Area administered by water utility
Changes in user behavior and demand	Changing land use patterns
Temporal access to water (water rationing, etc.)	Spatial access to water (distance to tap)
Changes in factors affecting demand	Demand for water

the efficacy of models was found to correlate strongly with the credibility, saliency, and legitimacy of those models to policy makers, properties which, especially for policies about complex systems, are highly dependent on the temporal and spatial scales of governance[17]. Therefore, the spatial scale covered by the model was bounded by considering the scale of the policymakers in Singapore. The scale of policy makers is considered to be relevant to processes acting on spatial scales that are on the order of magnitude of 10^1 to 10^5 meters; the model spans four orders of magnitude of spatial scale.

The Temporal Scales of Water Supply and Demand

The temporal scales of water supply and demand also cover at least eleven orders of magnitude, ranging from soil infiltration (which varies on the order of seconds) to groundwater accumulation (which varies on the temporal scale of millenia). Policy makers ought to consider events spanning at least three orders of magnitude: months, years, and decades. Sustainability science requires that the upper end of the range be extended to the century scale at least, and new communication technologies place events that occur on the order of days and weeks within the realm of saliency to policy. The lower bound on the spatial scale was set to 10m, and processes that occur on that scale match policies occurring on the order of days, weeks and months, and possibly even hours. On the order of 10^5 m, the temporal

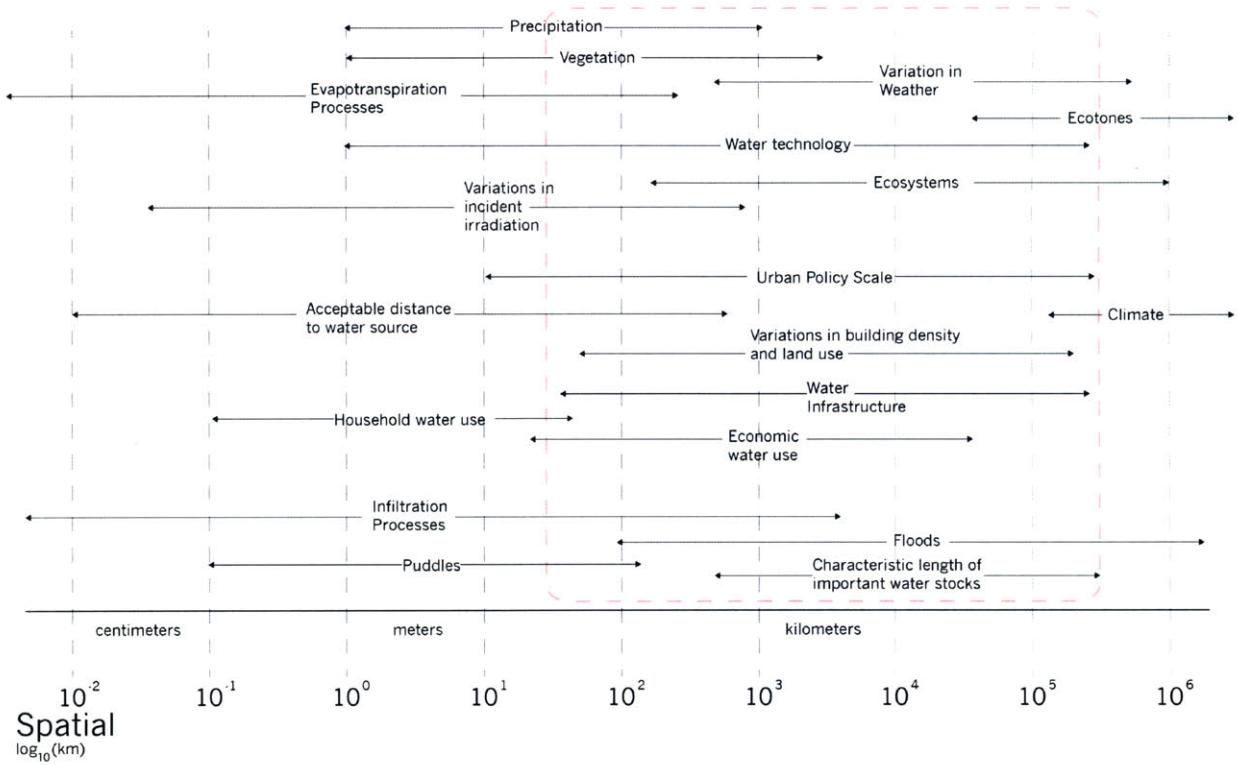


Figure 3-3: Spatial scales of processes related to water supply and demand.

range might also cover the temporal scale of days to decades: a precipitation even at the upper end of the water shed, 100km from a particular city, might be observed as a flood in the city within days of the precipitation event. However, if a data signal was available for a process on the spatial scale of hours, days and weeks, and then viewed over a longer period of time, the smaller spatial scales would be lost. Since this model is interested in the long-term trends and capacity of the system, the model should be able to simulate system behavior on the order of a century at least. Also, policies that affect the capacity of the system to supply water or alter demand over the long-term usually take at least a year to formulate. Therefore, the time step of the model (i.e. the unit of integration) is set to 1 month. Any processes occurring below the lower model bound or above the upper model bound, if considered within the model at all, do not exhibit endogenously modeled feedbacks or dynamic behaviors. Similarly, processes occurring at a scale larger than the upper bound of the model are considered exogenous.

Given the time scales depicted in Figure 3-3 and Figure 3-4 the important dynamic processes

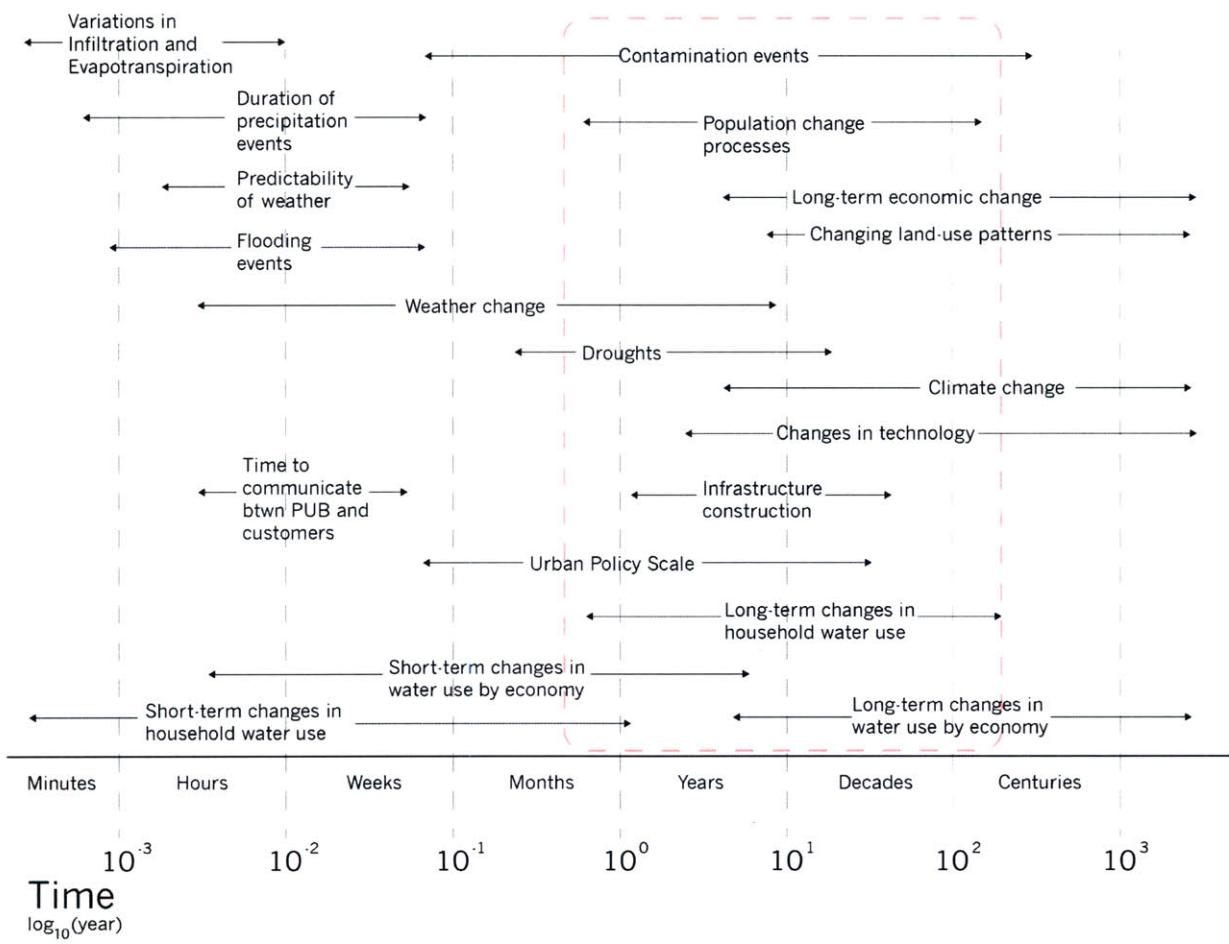


Figure 3-4: Time scales of processes related to water supply and demand.

within these time scales are summarized in Table 3.4, although this is by no means a comprehensive list, nor a list organized by hierarchy of importance. Separating water use into water use by population and water use by industry enables affluence to be more explicitly and internally calculated within the model. Use of water by industry and population represent the demand-side of the model. The supply side represents the physical carrying capacity to supply water. In addition to the water stock itself, the model includes a capacity to expand the water stock. The water stock will eventually limit growth. However, that stock can be expanded upon. In terms of water, the stock may expand naturally, but in terms of control processes internal to the system, the water stock can be expanded by investing in water infrastructure.

3.3 Model Formulation of the Dynamic Hypothesis

3.3.1 Water Resources

The literature suggests that the main water system properties that seem to characterize the system goals of interest are water consumption, water production and water quality (see Figure 3-5(a)). The system boundary for the model is defined as including the point of capture and ending at the point of disposal. Water consumption depends on population, economy, water availability, and technology. Water production depends on economic activity (financial support), local climate and land use, and technology. Water quality depends on land use, local industry and pollution rate, and the technological capacity to treat it. Ultimately, the resilience of an urban water supply depends both on physical and social parameters. Potential policy levers to increase the resilience of urban water systems are summarized in Table 3.3.

Table 2
Existing indicators of water supply sustainability

Physical availability	<ul style="list-style-type: none"> Annual withdrawal of ground and surface water as percentage of total available water^{a,b}
Water quality	<ul style="list-style-type: none"> Percentage of water sources that are protected^b Water quality <ul style="list-style-type: none"> Biological oxygen demand^{a,b} Concentration of faecal coliform^{a,b} Days per year contaminant levels exceed WHO drinking water standards^c
Service provision	<ul style="list-style-type: none"> Percent of the city with connections to the piped water system^c Per capita water consumption (liters per person day)^{b,d,e} Percent of supply points or taps that are functioning^e Water supply reliability (portion of time supply points are functioning)^{e,f} Water system losses^{b,e} Response time to install new connections^e Distance from source or treatment facility^b
Finances	<ul style="list-style-type: none"> Unit cost of water^{d,e} and affordability of services to the users^{a,g} Financial indicators for the water provider^e <ul style="list-style-type: none"> Cost recovery^{e,f} Cash balance^e

^a United Nations Division for Sustainable Development (2005).

^b Lundin et al (1997).

^c Alberti (1996).

^d United Nations Human Settlements Program (2004).

^e Stephen (2000).

^f Loucks (1997).

^g Morrison et al. (2001).

- (a) Existing indicators of water supply sustainability[19, Table 2]

Table 3
Factors that influence the percentage of the population with access to water

State variables	Stresses/pressures	Capacity to respond
Percentage of the population with access	<ul style="list-style-type: none"> Growth Changes in water use patterns Climate change Natural- and human-induced disasters 	Absorption: <ul style="list-style-type: none"> Un-used capacity Un-used supply Savings System redundancy
Quality of access:	<ul style="list-style-type: none"> Number of hours service is provided per day Number of people per connection Cost of water to user (time, \$, labor, energy) Infrastructure breakdown Changing regulatory standards Political pressures Supply capture by other users Financial risks 	Adaptation: <ul style="list-style-type: none"> Technical capacity to design, construct, provide, and manage water provision Financial capacity to cover the costs of providing access Governance capacity to organize, plan, and regulate the water system and its users Socio-political support

- (b) Summary of the main system properties that contributed most to water system resilience or vulnerability to external stresses[19, Table 3].

Figure 3-5: Tables from Milman and Short describing factors that contribute to the resilience of urban water systems, [19].

In order to adapt the dynamic hypothesis proposed by Tortajada to be more generalizable, the model drew from *Incorporating resilience into sustainability indicators: An example for the urban water sector*, a paper by researchers at the University of California, Berkeley[19]. In that paper, Milman and Short consider the vulnerability of urban water systems to acute or chronic changes that would affect the relationship of supply to demand. Milman and Short surveyed existing water metrics (summarized in Figure 3-5(a)) and found that they lacked an aggregated approach to assess system vulnerability, instead focusing on single parameters. For instance, although the annual percentage of freshwater withdrawals give an idea about the overall water stock, a water system may have sufficient freshwater but still not be providing reliable flow to taps. To fill in this gap in aggregated water system metrics, questionnaire intended to help municipal water managers think about and assess the vulnerability of their municipal water systems to different types of stressors, including climate change, natural disasters, changes in the economy, and social disruption. Since the vulnerability of water systems depends on many different types of stresses (summarized in Figure 3-5(b)), the questionnaire included sections eliciting qualitative evaluations of a water system's financial resources, political support, technical knowledge, and material infrastructure. Based on these qualitative answers, an aggregated assessment of the city's vulnerability to physical stresses was made. The intention of the work was a low-investment assessment of water system vulnerability such that it could be applied to many cities and contribute to a typology of water systems. The capacities described by Milman and Short were used as the conceptual basis for the dynamic formulation of balancing loops and carrying capacities in the System Dynamics Model for Singapore.

Carrying Capacity of the Local Environment

Any urban center under consideration is assumed to have access to a particular set of water resources to begin with. These water resources may include any or a combination of groundwater aquifers, rivers, lakes, and glaciers. Each individual water stock has an initial volumetric capacity that may be altered by technology. As long as people consume within the rate of renewal of the resource, the resource is renewable.

Biogeophysical characteristics of the local environment have important implications not only for natural inflow but also for infrastructure; they contribute to a characteristic regional natural carrying capacity. Given a particular type of water infrastructure technology, the water resource can be expanded only so much before the carrying capacity defined by the local environment is met.

As water infrastructure is expanded it becomes progressively harder to continue expanding. Originally, expanding the water stock required a dam and some pipes be built. Then more dams had to be added, more pipes, more employees, more complexity. In order to install infrastructure to increase the catchment area from 1/2 to 2/3 of the island required a dam built on a more complex scale than previous reservoirs since it was in an urban area (the Marina Barrage). Expanding catchment beyond this requires desalination and reclamation using reverse osmosis, both of which are extremely infrastructure intensive. In other words, as urban water demand reaches local carrying capacity, technology becomes greater to overcome the carrying capacity but the increase in technology becomes more material and energy intensive. This is the reference mode that all urban areas must follow to some extent depending on the natural carrying capacity and how easy it is to expand. In Singapore, the easiest catchments were installed and then a pipeline was built to Malaysia since it was the next easiest catchment to access. When that became threatened, more expensive catchments on Singapore were investigated and pursued to increase water security.

Although prior to the 19th century Singapore may have supported as many as a few thousand inhabitants, at the time of Sir Stamford Raffles' arrival in 1819, the island supported only a modest and stable population of a few hundred people who subsisted on foraging, fishing, and minor trade. Raffles facilitated the claiming of Singapore for Great Britain, and it was hoped that an international trading port could be established there to rival those of the Dutch in Indonesia. The 19th century saw the rapid growth of trade through the port and the deforestation of the island for agriculture, urban development, and eventually, industrialization. Today, nearly two hundred years after Raffles' arrival, the small island (length 30km, width

20km) supports a growing population of over 6 million and one of the largest economies in the world.

Water is essential to society and is metabolized by many different socioeconomic processes (not the least of which is life). By the mid-19th century, existing water supplies in urban areas struggled to keep pace with the rapidly growing population and economy[20], and this shortfall began to exhibit itself as problems in sanitation, polluted waterways, and fluctuating supply. By 1850, city planners had take the first steps to build a reservoir and construct infrastructure to supply this water directly to households in most of the urban area, and by 1868 this reservoir, later renamed MacRitchie, had been completed.

Table 3.5: Water sources leveraged for urban water supply

Water Type	Source	Natural
Freshwater	Precipitation	Rain Snow Fog Hail Groundwater Surfacewater
Other	Seawater Wastewater	Desalination Reclamation

The earliest sources of freshwater in Singapore were streams and wells. By the end of the 20th century, water resources had been expanded to include wastewater reclamation and desalination. Initially, water catchment area is localized to water sources in the near vicinity. Singapore used island catchment area until 1930, at which time it expanded its water catchment area to include the catchment area of two rivers in Johore. This provided it sufficient capacity to continue supplying water for the next 40 years, at which time Singapore began investing, at considerable expense, in the conversion of coastal estuarine lands to reservoirs. Even though 30% of the island catchment area has yet to be leveraged for water collection, Singapore has begun investing in reclamation and desalination technologies. My hypothesis for this phenomena is that the earlier land reclamation for water catchment was of a different

financial intensity than later stages of land reclamation, and that expanding collecting into a larger catchment area has required technology with a financial intensity for expansion similar to that for desalination and reclamation technologies. This hypothesis seems to be supported by the data used to make Figure 3-33(a) and Figure 3-33(b).

There are really only two sources of water in the Singapore system: water collected in the watershed, and water produced from seawater. There are three types of processes by which this water is sourced: water collected from nature, water desalinated from seawater, and wastewater cleaning.

Natural inflow will be modeled as both exogenous and endogenous. The exogenous input is the precipitation signal. Precipitation depends on both global and local processes and is highly complex. Local processes that affect natural inflow may be modeled endogenously although for now they are considered exogenous.¹ Non-natural inflow is inflow that arises from technological adjustment to the water cycle. Non-natural inflow involves resources that can only be extracted through application of technology, including rainwater harvesting, reclamation of waste, dam building, mining, diversion of water from distant watersheds, desalination, etc.

The figure below describes the major stocks and flows of water within the city of Singapore. Each stock of water represents physical water that gives rise to inertia within the system. The size of the stocks, their capacities, and the flows between them may give rise to lags and delay that, if managed improperly, could give rise to water availability relative to demand.

¹Examples of biogeophysical parameters of water provision that are affected by urbanization include runoff rate, evapotranspiration rate, contamination of surface waters by pollutants. These parameters could be disaggregate in the future to explore feedbacks between different types of environmental impact in the watershed; for now, if urbanization is expected to change these parameters, model sensitivity to the aggregated parameters affected by those changes could be examined.

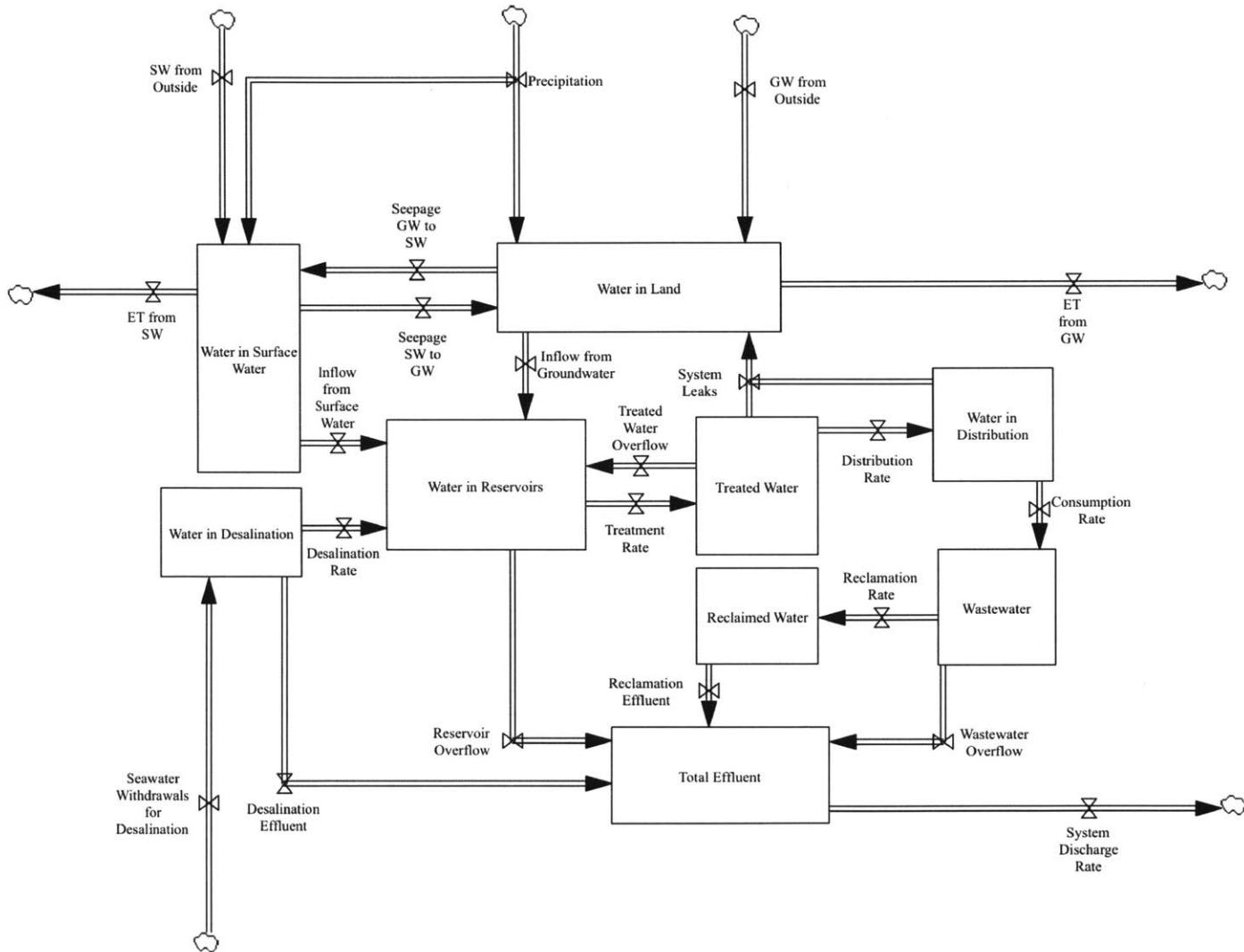


Figure 3-6: Schematic summarizing the water resources stocks for Singapore.

$$\dot{Q}_{Inflow} = \dot{Q}_{Natural} + \dot{Q}_{Technology} \quad (3.1)$$

$$\dot{Q}_{Natural} = \dot{Q}_{Precipitation} + \dot{Q}_{Groundwater} + \dot{Q}_{SurfaceWater} \quad (3.2)$$

$$\dot{Q}_{Technology} = \dot{Q}_{Desalination} + \dot{Q}_{Reclamation} \quad (3.3)$$

$$\dot{Q}_{Outflow} = \dot{Q}_{Evapotranspiration} + \dot{Q}_{Unaccounted} + \dot{Q}_{ConsumptiveUse} + \dot{Q}_{Effluent} \quad (3.4)$$

$$\dot{Q}_{IntermediateEffluent} = \dot{Q}_{Inflow} - \dot{Q}_{Evapotranspiration} + \dot{Q}_{Unaccounted} + \dot{Q}_{ConsumptiveUse} + \dot{Q}_{Effluent from Desalination} \quad (3.5)$$

$$\dot{Q}_{Effluent from Desalination} = (1 - \eta_{Desalination}) * \dot{Q}_{Seawater} + \quad (3.6)$$

$$\dot{Q}_{Desalination} = \eta_{Desalination} * \dot{Q}_{Seawater} \quad (3.7)$$

$$\dot{Q}_{Reclamation} = \eta_{Reclamation} * \dot{Q}_{Effluent} \quad (3.8)$$

Capacity to Reuse is equal to the quantity (and quality) of Intermediate Effluent, reduced by the efficiency of the process:

$$\dot{Q}_{Effluent from Reclamation} = (1 - \eta_{Reclamation}) * \dot{Q}_{Effluent} \quad (3.9)$$

Water Resources is formulated as a stock. It is initialized such that the quantity of water at the initial time is high enough to meet socioeconomic demand, but the ratio of maximum outflow to socioeconomic demand is close to one, since soon after time zero, a drought decreases the stock of water resources to the point that it is not sufficient to meet demand.

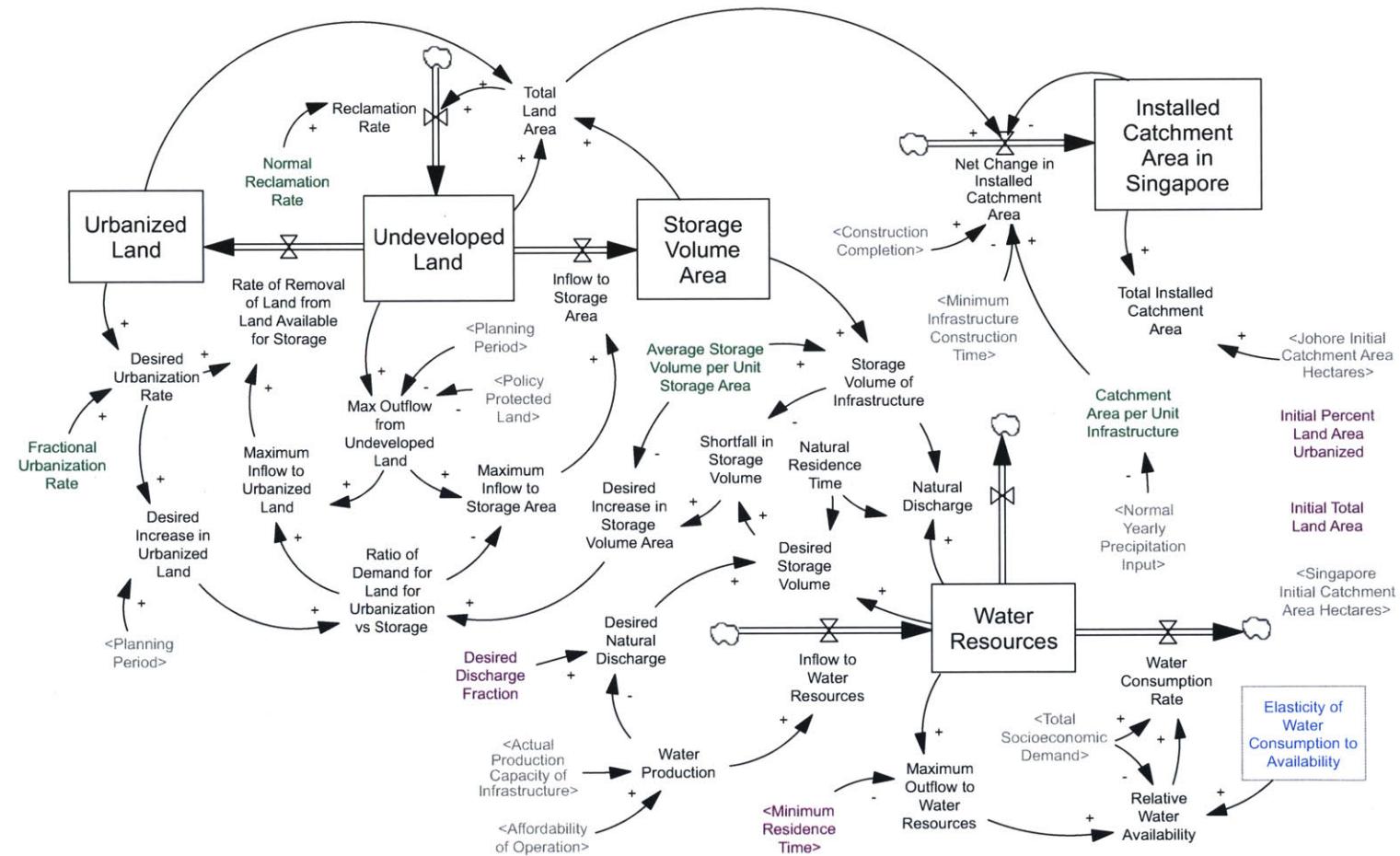


Figure 3-7: Figure showing the model structure for water resources

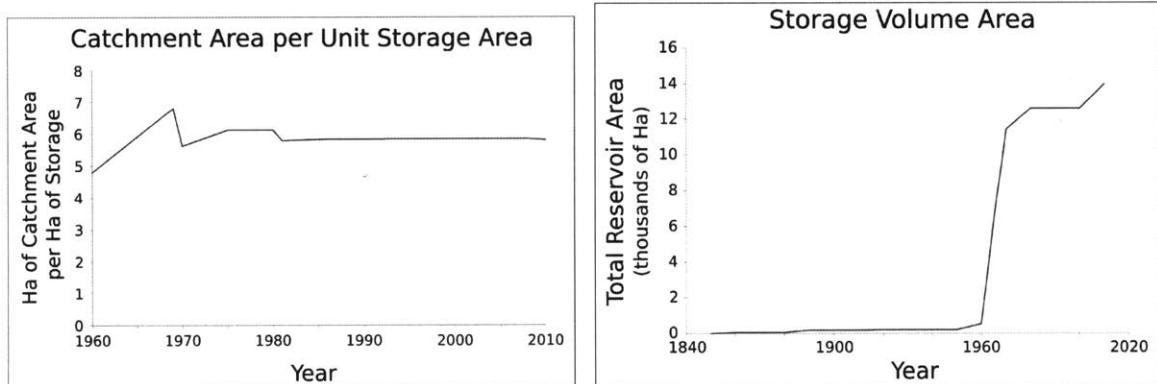
Water inflow from precipitation is collected in reservoirs. With the completion of the Marina Barrage in 2008, Singapore now has installed collection of water from two-thirds of the island area. However, the water infrastructure also includes the use of water in Johore, Malaysia. Johore has a similar climate to Singapore and receives similar precipitation. In 2009, PUB reported that 20% of annual supply was met with water from Singapore's internal catchment and that 40% of water was met by importing water from Malaysia[8]. The catchment area of Johore must be at least twice as large as the catchment area in Singapore, and likely larger. In 2009, total water consumption in Singapore amounted to about 1.3 billion m³/year, so water imported from Malaysia accounted for about 500 million m³/year. In 2005, Malaysian water counted for about 60% of supply. Demand in 2005 was about the same as it was in 2010, so the capacity of catchment in Johore must be at least sufficient to supply 750 million m³/year. If Johore also receives an average of 2m/year of rainfall, then the catchment area of Johore must be at least 375km². The installed catchment area of Singapore at the start of the model is therefore about 70% of total island area, including catchment in Johore (and possibly higher)[8].

Table 3.6: Table summarizing biogeophysical parameters that affect natural inflow

Climate
Topography
Evapotranspiration
Runoff rates
Catchment Area

3.3.2 Residence Time and Land

Reservoirs are often one of the first types of water infrastructure installed near cities. They alter several parameters of local water systems and are relatively easy to construct. First, reservoirs increase the capacity of the region to store water, which increases the natural residence time of water in the system. Second, this water storage generally generates a larger pressure differential than would exist otherwise, and the water in the reservoir has greater gravitational potential energy. This energy can be harnessed as pressure to drive water



(a) Ratio of catchment area (calculated) to storage area over time.

(b) Surface area of storage reservoirs.

Figure 3-8: Parameters affecting the pressure of water infrastructure on land. (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

through the water infrastructure downstream, and can also be harnessed to do work when converted to mechanical or electrical energy. Additionally, a large water stock adds inertia to the system and increases system stability by damping the effects of short term fluctuations.

Lakes and ponds are examples of naturally occurring reservoirs and are formed when a water flow encounters a depression in topography capable of storing water. The simplest reservoir therefore requires no moving parts and can be constructed by altering the local topography and geology. This relative simplicity of design and multi-functionality make reservoir construction an attractive first step for water infrastructure expansion.

The importance of changing the local storage capacity and natural residence time in Singapore are apparent when one considers that the precipitation of Singapore over the island each year is sufficient in quantity to provide all (or at least a majority) of the water supply required to meet demand (the derivation is described in Section A.2.1). In other words, volumetric flux into Singapore each year, even when adjusted for the water lost to evapotranspiration and ecosystem services, should still be sufficient to contribute more to Singapore's water supply than it does. That it does not suggest that there are unsurmountable challenges in the collection of precipitation for socioeconomic water supply.

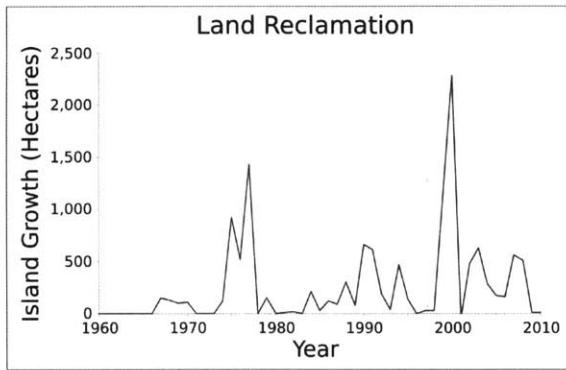


Figure 3-9: Figure showing historical land reclamation in Singapore, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8]. Compare with Figure 2-2 to see the correlation between spikes in land use and spikes in material consumption. In some cases a delay is observed which suggests a time delay between the obtaining of the material and its construction.

The challenges to leveraging a higher percentage of Singapore's total water inflow from precipitation are intricately related to limited availability of land. Singapore is an island surrounded by seawater, and the only natural inflow of freshwater to the island is in the form of precipitation flux over the surface area of the island. Therefore, natural freshwater flow is inherently limited by land. Limited land area also affects the storage capacity of the island, with important implications for residence time. The first is an issue of storage. Water storage occupies an amount of land that scales linearly with the desired storage capacity, and for a relatively small island with relatively shallow topography and high water demand, increasing water storage has a significant impact on socioeconomic land development². The second challenge with accessing more of Singapore's precipitation input lay in the character of the land area in question, and challenges of collecting water that fell on it. For instance, a significant fraction of land area is low-lying and coastal, and occupied by mangrove or other estuarine ecosystems. The difficulty in collecting water falling on this surface lies in the fact that the distance and slope to the sea is so small as to make water collecting easy to design. Moreover, by the time the government became interested in tapping into more of the watershed, much of this coastline had already been developed for important international trade.

Even beyond storage, water infrastructure is relatively land hungry compared to infrastruc-

²Desired Storage Area = Desired Storage Volume/Average Height of Reservoir, and since Volume has units of length³, and Height has units of length¹, then, for a given Average Height, as the Desired Storage Volume increases, the Desired Storage Area must increase linearly.

ture for other resources. Transporting electricity can be accomplished over relatively thin cables which can be suspended in the air and the land nearby developed for other purposes. Natural gas is more similar to water in the sense that it also requires physical containment and more physical infrastructure than is required for electricity, but because it can be pressurized, it requires a smaller area than would be required otherwise. Water, however, for all intents and purposes pertaining to general freshwater provision, is an incompressible fluid. The infrastructure requirements for water storage and transportation must therefore scale with the volume of water required to meet demand.

Residential and commercial development compete with water infrastructure requirements for the very limited land area that is available for development[36]. This competition for dwindling land generates much pressure for a government interested in growing population and economy. The importance of land to development is evidenced by the large investments in financial and material resources over the past 50 years, by the Singaporean government, into projects expanding coastline (see Figure 3-9). However, cognizant that water resources would need to keep pace with socioeconomic water demand, and with ambitious expansion goals for population and the economy, the Singapore government had to carefully balance land development policy between development goals and water resources, and water provision has played an important role in the formulation of land development policy over the past 50 years.

Land use change is driven by socioeconomic processes, as discussed in Section 2.1, and these changes in land use also drive changes in socioeconomic demand for water. Singapore's sociometabolic regime is still in the sociometabolic regime of industrial transition. Pre-fossil fuels, island inhabitants operated within a dynamic equilibrium with water resources on the island. Within 100 years of the first reservoir construction, Singapore expanded its water resources to imports from Malaysia and was no longer limited by the carrying capacity of the island. In the 50 years since Singapore's independence, the development of technology and continued relative abundance of fossil fuels has opened up two entirely new sources of water: desalination and wastewater reclamation[11].

For instance, some of the reclaimed land has gone to increasing area for water storage[36, 1]. In the 1980s the government set aside the interior of the island as well as land adjacent to reservoirs as protected area, a policy motivated by recognition that the dense urban development characteristic of Singapore could easily increase the concentration of contaminants in the island's naturally-collected water supply[20] (see Section A.2.3. In sacrificing some of the land around these water supplies to protect quality, the pollutant load (and expensive costs of treating it) could be significantly reduced, and the government has even been able to add commercial value to these protected areas by establishing and promoting parks and recreation areas there.

Changes in land use have other important effects on water supply as well. Vegetation cover, type of vegetation, and built area all vary with the type of land use and lead to changes in runoff rates, evapotranspiration, residence time of water in the watershed, and water table height. Increased runoff rates lead to more flooding and reduced water quality and adversely affect ecosystem diversity and health. The water quality of urban surface waters is also compromised by pollutants that are absorbed during runoff, such as substances leaked from motor vehicles, which furthermore reduce water quality beyond what it would be otherwise by reducing the capacity of ecosystems to naturally filter the water even before it is treated. Changes in land use and the character of the built environment have even been found to alter precipitation patterns around urban areas[52, 32].

The form of precipitation alters the residence time of water in the system: snow will be stored and then released into the system at a later date (leading, for instance, to high river levels in the spring); rainwater will enter the system and some fraction will run off and be collected in streams and another fraction will seep into the ground. Some major urban areas depend on meltwater from glaciers and therefore it could be useful to model the relative storage times of different types of precipitation. It was not done so for Singapore, since Singapore mainly receives its precipitation as rain. Instead, if glacial meltwater is a significant source of freshwater to an urban area and it is important to consider changes to that flow (such as those that might arise from increasing average temperatures), the average yearly input

could be changed to reflect higher and lower surface water inputs over time. Similarly, for some cities, groundwater will be an important source of water; Singapore's water table is considered insignificant relative to it being used as a water source. Whether or not precipitation eventually ends up as land flow though, it is reasonable to assume that most of it goes either into surface water or groundwater, but may be evaporated before it enters the collection of the water system. On the other hand glaciers and groundwater operate on much longer time scales than surface water, and are not currently included in the system boundary.

3.3.3 Socioeconomic Demand for Water

Carrying Capacity of Water to Population and Economy

As population and economy grew in Singapore, the demand for water grew beyond what it would have been otherwise. The model endogenously includes socioeconomic activity to capture the feedbacks between water availability and socioeconomic activity.

Taking a closer look at the model formulation of socioeconomic activity, at any given time, both population and economy (the socioeconomic system) have access to an amount of water that depends on the natural residence time of the system, and the current state of their water production, collection, and storage technologies³. As the demand of water approaches the amount of water that can be taken from this stock of socioeconomic water, the availability of water relative to demand will drop. This shortfall will put pressure on people to increase their water resources. If water availability actually falls below what is required to meet demand, people might leave. Most people will simply reduce their demand relative to what it would be otherwise and/or will be more willing to spend more money for water. The situation is similar for economy. Economy takes much longer to adjust demand, however, and is more sensitive to water availability.

³Water technology includes everything from a bucket to carry water from the river into a house or a desalination plant that produces pure water from seawater using reverse osmosis and other advanced techniques.

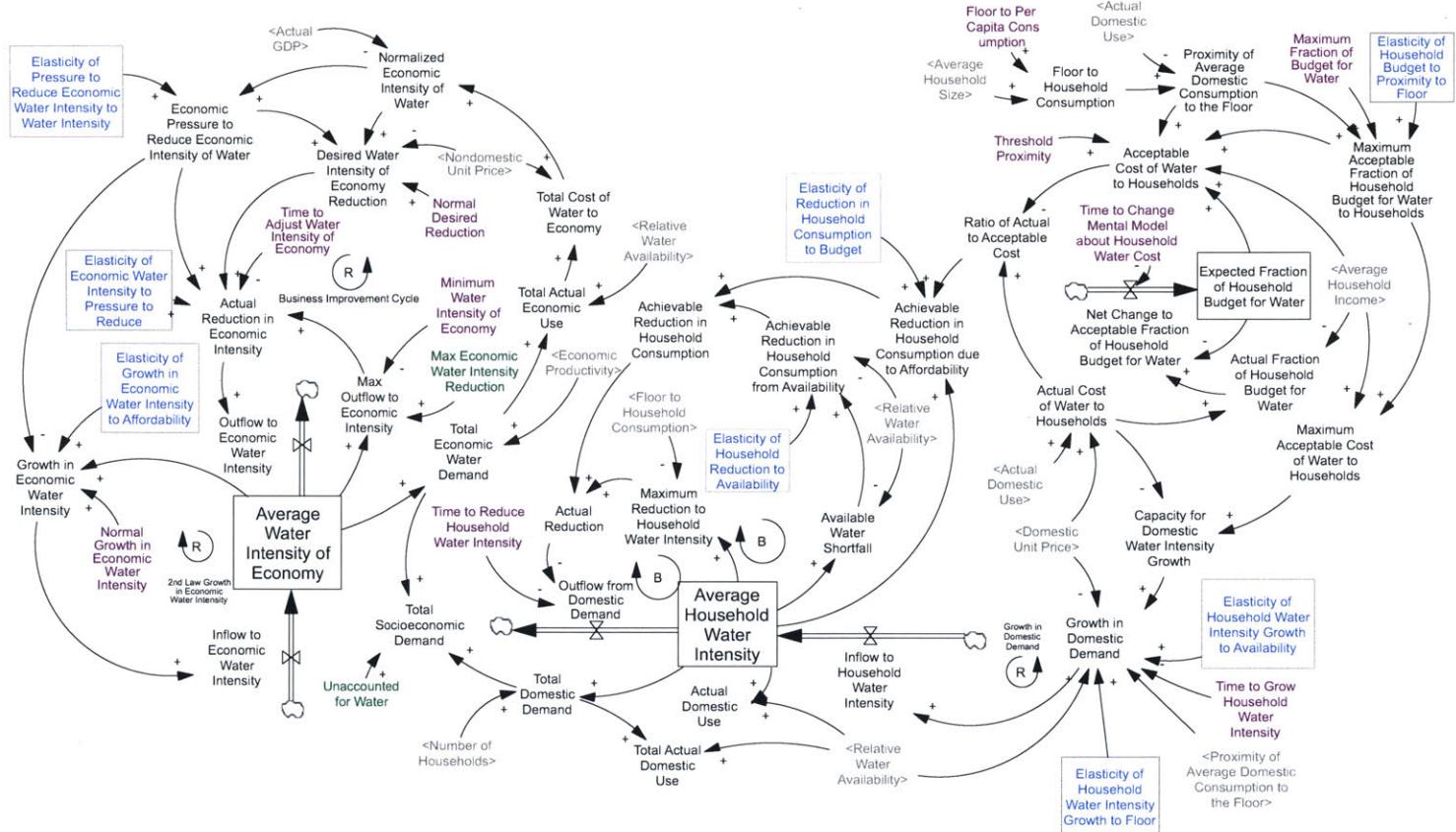


Figure 3-10: Figure showing the model structure for socioeconomic water demand

Changes in socioeconomic water demand are driven by changes in processes that consume those resources. Population will grow. As population grows, economy grows, the local attractiveness grows, and more people come[39]. Both people and economy require water resources. The model disaggregates socioeconomic metabolism into demand driven by affluence and demand driven by the economy, such that change in either population and domestic consumption patterns or change in economy and economic water use will drive change in total socioeconomic water demand. Both economic growth and population growth increase the demand for water beyond what it would be otherwise, all other things being equal. There is also a normalized demand for water from population and economy, such that even if the size of the population and economy remained constant, if the change in normalized demand changed, the socioeconomic demand for water would change.

Socioeconomic demand is the demand arising from all of the socioeconomic activities within the city boundary. Each person has a per capita water consumption. This per capita consumption is related to the direct consumption, by individuals, of goods and services and the indirect consumption of resources consumed during the manufacture, production, and distribution of aforesaid goods and services.

$$Demand_{TotalSocioeconomic} = Demand_{TotalPerCapita} * Population \quad (3.10)$$

Populations and economies both undergo exponential growth and decay[21]. Growth in population and economic size are each driven by a reinforcing loop that also drives growth in resource consumption. However, both populations and economies do not grow outside of a system: a growing economy can support a larger population and growing economy requires a larger population relative to what it would otherwise. The links between population and economy include both a reinforcing loop (affluence increases population inflow) and balancing loops (affluence reduces birth rate; the size of the economy limits the size of the population and vice versa). The exact nature and carrying capacities associated with these two processes are outside the scope of this thesis. Suffice it to say that they do interact. For the purposes of this thesis, however, the growth rates of economy and population are approached exogenously.

For industry, industry seeks to become more efficient in terms of how much water per dollar

Table 3.7: Table summarizing processes that contribute to socioeconomic demand

Sector	Type of Consumption	Examples of Services
Domestic	Direct	Cooking and drinking Flushing toilets Washing clothes Irrigating the lawn
	Indirect	Clothing Growing or processing food used within the home
Nondomestic	Economic	Agriculture Manufacturing and other industry Commercial food production
	Societal	Water used to maintain government and political and social bodies Water used in production of infrastructure such as roads Maintenance and irrigation of public spaces

it is using. When water is cheap, water will be wasted but either way the pressure to be more profitable is something that drives companies much more than households, on average. If the economy grows faster than water demand is reduced through increased economic water efficiency, then demand in total will grow.

Formulating Domestic Demand

Consider as direct consumption the consumption which requires an individual to actively obtain water from water infrastructure for their personal use. This would include water used for flushing the toilet (whether a mechanical or automatic flush system), washing hands, and drinking. Water for cooking, water for washing dishes, and water for washing clothes are also examples of direct consumption, but are trickier to associate with an individual and likely lead to variations within a household. For instance, if one person does all the cooking for the household, then that person is the direct consumer of water and would have a higher water footprint than other members of the household. The household is therefore a more useful

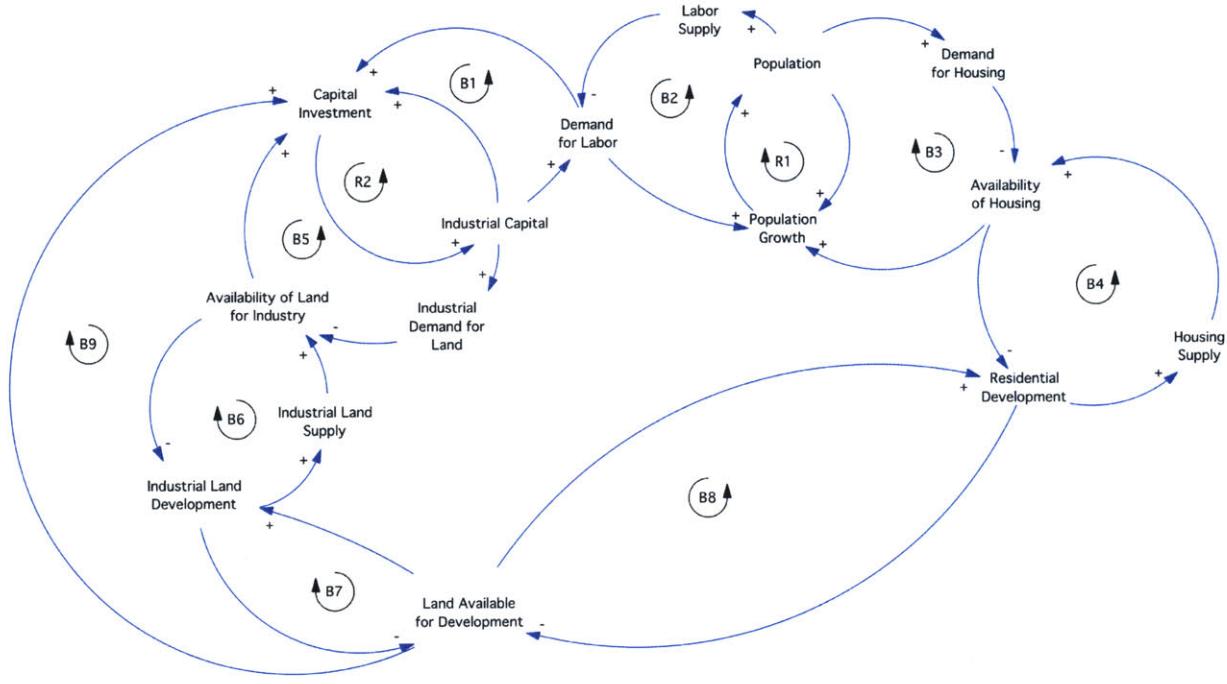


Figure 3-11: Causal loop diagram of feedbacks between society and the environment

unit for water used residentially. What about water used by businesses? If an individual flushes a toilet at their place of employment, should that toilet flush count for their individual use or the company's use? Since the household is a more useful unit for residential use, it provides a meaningful delineation between water used by individuals at their homes and at their workplace. Direct consumption by workers at a workplace is essentially an input into the eventual product or service of that business. Therefore, households and businesses are the units for which direct consumption of water is evaluated.

$$Demand_{Total\ Socioeconomic} = Demand_{Domestic} + Demand_{Economic} \quad (3.11)$$

$$Demand_{Domestic} = Intensity_{Household} * Number_{Households} \quad (3.12)$$

Including indirect consumption creates a more comprehensive view of the resource demands of urban metabolism, since direct consumption only accounts for a small fraction of overall per capita water demand. Indirect water consumption includes the consumption of goods

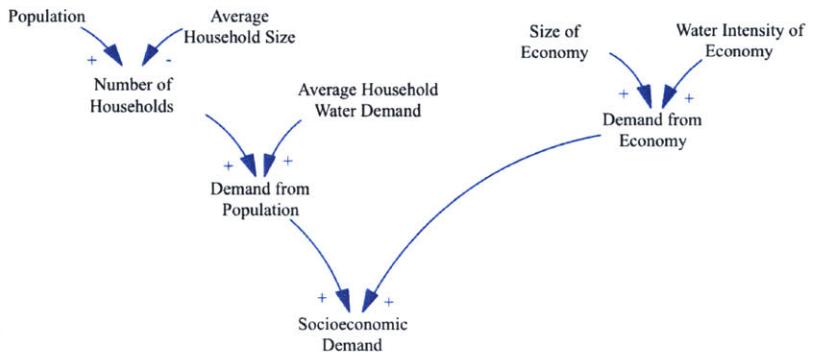


Figure 3-12: Contributions to socioeconomic water demand from domestic and nondomestic sectors.

and services without any apparent water in them, but in the production of which water was used. For instance, if a local economy is dominated by retail shops selling clothes, then these businesses do not themselves directly consume water. However, the production of clothes, from start to finish, requires water at many stages in the process including water for irrigation or drinking to produce natural fibers, water used in chemical treatment or fiber alteration, and potentially construction of textiles from these fibers. These retail stores indirectly consume water by providing a market which increases demand for intermediate products which increases demands for raw materials and processes that require water.

Exchanges with areas outside of this boundary are aggregated into bulk resource flows. These bulk resource flows could be extended to include indirect water consumption in the future, which is an important step for evaluating inter-city and international sustainability policy. However, the scope of this model is the scale of a single city and therefore the model boundary has been drawn around the city boundary.

Water consumption in Singapore has increased for both the domestic and nondomestic sectors over the past half-century. Normalizing domestic demand by population on the one hand and the number of households on the other, it is apparent that the increase in domestic water consumption is not only due to the increase in number of households or population alone. Normalizing nondomestic demand by economic activity shows that although the total water

consumption by the nondomestic sector has increased, the water intensity of the economy has also dropped; the economy is becoming more water efficient. Studies have shown that resource demand is positively correlated with affluence, and there is a simple causal loop structure to represent a potential causal behavior to describe this observation.

Population in Singapore increases over time. Although the reference mode does not obviously follow an exponential growth curve, we know that population growth and decay is proportional to the population at any time. Moreover, population provides the system with inertia. There are several different processes that flow into the stock of population, such as births and immigrations, and similarly there are several different processes that flow out of population, such as deaths and emigrations. For this model, we aggregate these processes as net inflow and net outflow.

Domestic water demand is water consumed for residential use. Domestic use can be normalized both by total population and by household. Normalizing demand by both, it is observed that both per capita and average household water demand increase over time. While some services associated with the domestic use of water, such as bathing and hygiene, are closely associated with individual behavior, other services such as cooking, cleaning, and watering the lawn are associated with household behavior. In some ways, bathing and hygiene are also associated with the household since some of these individual services make use of communal household technologies such as type of shower head and washing machine. Since many water-conserving technologies and policies target the household, that is the unit of domestic consumption used in this analysis, in order to facilitate the future evaluation of water policies or technologies. That household members tend to share a level of affluence and its correlated increase in resource demand supports the use of the household as the unit of analysis. Furthermore, the household unit is often used in other types of material and energy analysis.

To provide comparison, however, we include a normalization of household water intensity by capita and by household. Tellingly, the average household demand shows more oscillation than per capita demand, and in particular, shows dips that coincide with years of low pre-

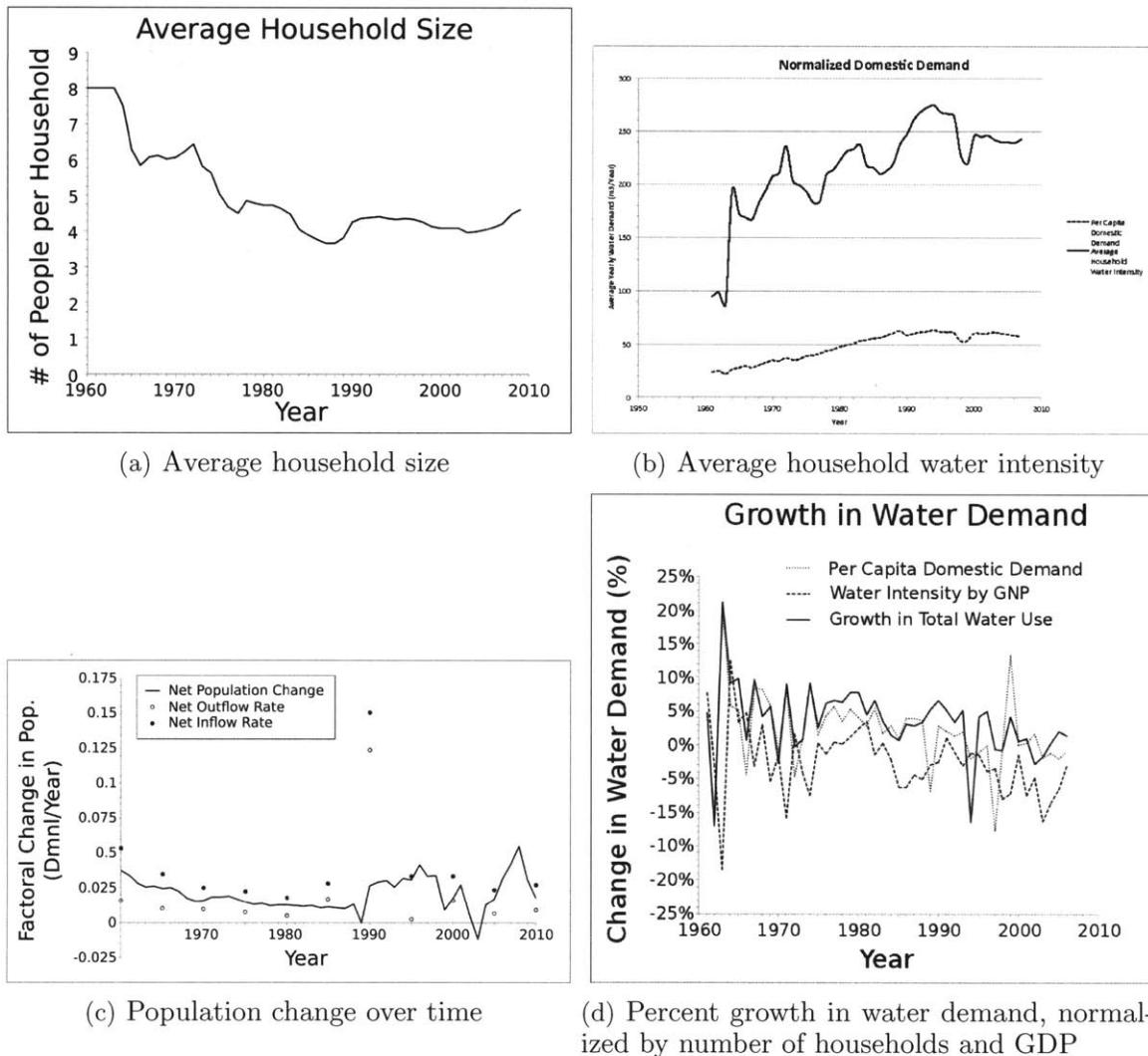


Figure 3-13: Historical values for factors pertaining to changing domestic and nondomestic water demand in Singapore, (*Graphed using data from PUB Annual Reports*) [2, 3, 4, 5, 6, 7, 8].

cipitation (which are noted in Figure A-5). Therefore, the two processes that are considered to be at play in household demand are, first, an increasing affluence and with it, an increase in the resources with which one can try to achieve an increased quality of life, and second, a sensitivity to actual water availability.

Both household and per capita domestic water demand increased historically, as observed in Figure 3-13. However, examining the domestic water demand normalized by number of households relative to the domestic water demand normalized by population shows two differing behaviors. Interestingly, the household-normalized demand shows oscillation whereas the

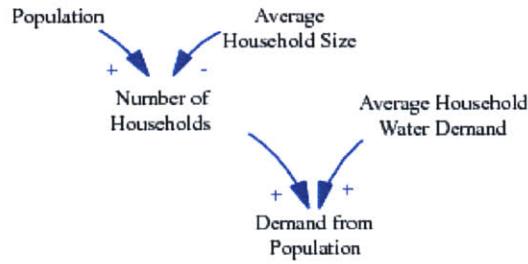


Figure 3-14: Causal loop diagram of household demand.

population-normalized demand is relatively smooth. The local minima in Average Household Water Intensity observed in Figure 3-13(b) coincide both with historical increases to water price (see Figure 3-30 and to times of drought (recall Figure 1-2(b)). To describe the growth behavior, a reinforcing loop was included to model growth in the stock of Average Household Water Intensity (see Section 2.1.2 for more information on increasing per capita demand and quality of life). To describe the oscillations, balancing loops with time delays were required; the coincidence of minima with times of relative water scarcity and changes in water pricing suggested that availability of resources and affordability of the resource played a role in demand.

The average water demand is formulated such that there is a limit to the water that is consumed based on availability and also on demand. If water is available, the average household demand will grow as far as the water availability allows. In the municipal water system, this availability is the total availability of the system. If water provision has a cost, then the household water demand will have a ceiling that depends on availability and also on affordability. The affordability is determined by the average household income, and water price. The acceptable water price is formulated as a floating goal that involves an expected water price, such that the mental model about the expected cost to budget has inertia and involves a time delay, the Time to Change Mental Model about Household Water Cost. That time constant, as well as time constants associated with reduction in household demand and growth in household demand, provide the inertia that give rise to oscillations.

Average household demand is a function of the number of services used per household as

well as the water use per service. The floor of water consumption for any place depends on the water use required for the bare minimum of survival. What is defined as the bare minimum of survival depends on the place. There is an absolute level, which is considered to be 5/L/cap/day ($1.8 \text{ m}^3/\text{cap/year}$), which is really the bare minimum required for surviving, but not doing much else, and includes cooking and drinking water. Health and survival increase dramatically with increases in water use up to 25L/cap/day ($9\text{m}^3/\text{cap/year}$). Quality of Life tends to rise with Per Capita Water Consumption up to about 50L/cap/day ($18\text{m}^3/\text{cap/year}$)[67]. After this point, any additional increase in water consumption is associated with a much smaller increase in quality of life. In other words, the effect of increasing water consumption on increasing quality of life follows the law of diminishing returns and is non-linear. These figures consider required for direct consumption of water, such as cooking, cleaning, bathing, and other household services. It does not include the water required for societal services like government or the economy, and also does not consider the water required to produce other essentials such as food and clothing. Countries around the world fall between low values ($10\text{L}/\text{cap/day}$) and high values ($300\text{L}/\text{cap/day}$)[92]. When water associated with other services is included, the average water consumption can increase to as high as $1000\text{L}/\text{cap/day}$.

Each household has a certain level of affluence that depends on the average household income, and other costs. This sets the carrying capacity of household finances for domestic water consumption and is formulated here as a fraction of budget spent on water, such that:

$$\text{Acceptable Household Budget for Water} = \text{Acceptable Fraction of Household Budget for Water} * \text{Income} \quad (3.13)$$

This fraction of the financial budget for water use is the goal to which the household water use should seek (it may be a floating goal, but for now is modeled as a static point). All other things being equal, if the budget for water use suddenly increases, the average household water use should start to increase and level off as it approaches the acceptable household budget. If the Water price saw a sudden increase, we would expect the average household water intensity to decrease to approach the acceptable household budget. In both cases,

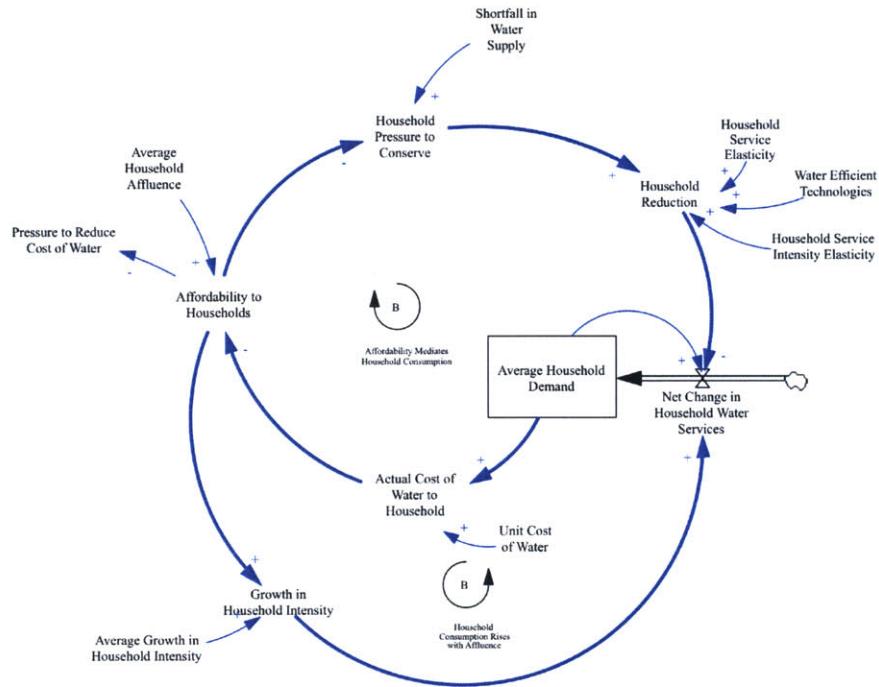


Figure 3-15: Causal loop diagram of processes affecting household demand.

while the consumption is assumed to be able to adjust immediately, the demand does not.

The model is found to be sensitive to both the Time to Change Mental Model about Household Water Cost. The Household Water Cost is normalized relative to household income, such that the decision variable is an Expected Fraction of Household Budget for Water. This budget is formulated with a carrying capacity of $ExpectedFractionofBudgetforWater * AverageHouseholdIncome = AcceptableCostofWatertoHouseholds$.

Increase to Acceptable Water Price If relative water availability is above one, then the acceptable price for water will decrease relative to what it would be otherwise. On the other hand, if relative water availability drops above 1, then the acceptable water price will go up. The acceptable price of water will depend on normalized consumption; if household water consumption is very close to the floor of consumption, then the acceptable price for water will be such that at most the acceptable fraction of the household budget would be 50%.

The acceptable water budget also depends on other factors; most particularly, on Relative Water Availability. The more available a resource is, the less economic value it has. If water is understood to be very available, people will not be willing to spend much on their water. As the perceived availability drops, the amount of money people will be willing to spend on their water increases. Therefore, if the Relative Water Availability drops significantly, then the Acceptable Cost of Water to Households will go up beyond what it would be otherwise.

The sensitivity of Acceptable Cost to Water Availability depends on the Proximity of consumption to the Floor to Household Consumption which depends on the Floor Per Capita Consumption. The Floor is a variable that captures the fact that every person requires a certain amount of water for survival; this is the Floor. The Floor depends both on survival and on socioeconomic factors. The absolute Floor to Per Capita Consumption is around $1.82\text{m}^3/(\text{year} * \text{person})$, which is $5\text{L}/(\text{day} * \text{person})$ [67]. The input to the model was formulated as a socioeconomic Floor, such that the Floor input to the model is higher than the absolute minimum of $1.82\text{m}^3/(\text{year} * \text{person})$. The Floor to Household Consumption affects the Acceptable Cost of Water through the Proximity to the Minimum Domestic Water Intensity. The Proximity to the Minimum Water Intensity is formulated as a ratio of the Floor to Per Capita Consumption to Actual Domestic Use, such that as the Floor goes up, the Proximity to the Floor Goes up, and as the Actual Domestic Use goes up, the Proximity goes down.

This model also depends strongly on the Elasticity of Household Budget to Availability, which is used to find the Maximum Acceptable Fraction of Budget for Water to Households. The Maximum Acceptable Fraction of Household Budget is used to find the Acceptable Cost instead of the Expected Fraction once the Threshold Proximity (of Household Consumption to the Domestic Floor) has been surpassed.

The Maximum Acceptable Cost of Water to Households is what is used to limit the Growth in Domestic Demand. In addition to the increase in water consumption driven by a desire

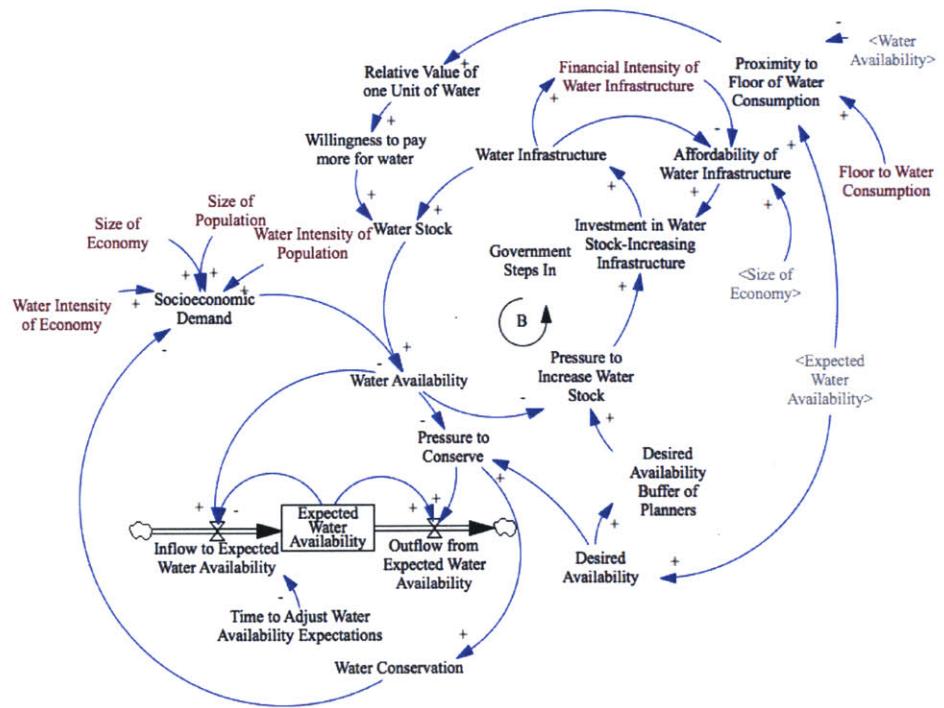


Figure 3-16: Causal loop diagram depicting the feedback between water availability and price.

to improve quality of life and funded by increases in affluence over the observed period, the inexorable consequences of the 2nd Law of Thermodynamics⁴ require that over time, all other things being equal, water demand will tend to increase due to inefficiencies that arise in use over time. These inefficiencies include deterioration of technology and profligacy in use when water seems very available. The Expected Fraction of Household Budget for Water was found to not give rise to the kind of oscillation observed in Average Household Water Intensity.

The Elasticity of Household Budget to Proximity to Floor was determined through sensitivity, as was the Maximum Fraction of Budget for Water. When the Maximum Fraction of Budget for Water was set high, then the water demand growth rose to values higher than historical and when too low, the average household water intensity never rose high enough. The Maximum Fraction of Budget for Water may depend on the city and would be interesting to compare between cities. These two balancing loops (Affordability and Availability) keep the Average Household Water Intensity from growing indefinitely due to the reinforcing loop

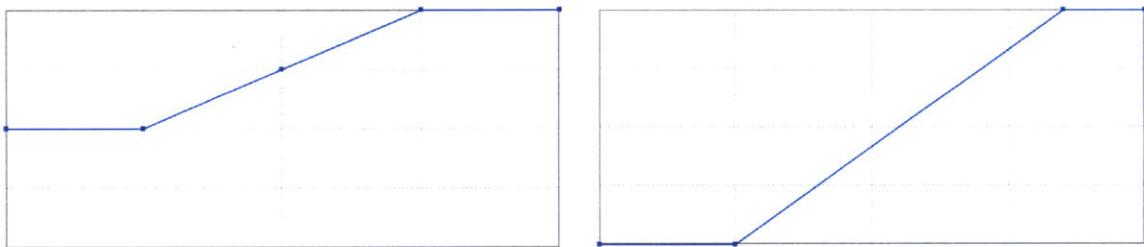
⁴Entropy is always greater than or equal to zero.

driving Growth in Domestic Demand. The Average Growth in Domestic Demand is limited by the availability of water and also by the Proximity of the water to the floor.

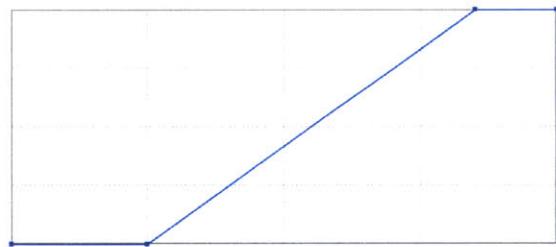
Reduction in average domestic water intensity is driven in part by availability of the resource and in part by the limits to a households financial resources. If water availability is less than the demand, then consumption will be less than is desired. This will generate pressure to reduce socioeconomic demand, which typically results in a reduction in average household demand rather than a reduction in people. However, household demand depends on the stock of services and technologies which a household is accustomed to using and requires time to adjust, so the desired decrease in average household demand might be more than can be achieved. Assume that within any given year, a family can only decrease their water demand by at most 25%. If a 25% reduction is not enough to compensate the shortfall between desired and actual consumption, then this will generate a pressure to find greener pastures. If the pressure to reduce water is greater than the amount by which consumption can actually be reduced, then the pressure will be alleviated by a combination of reduction and leaving the city.

People have been found to be more likely to pay more for water than to leave the city when water is scarce⁵. Part of this extra cost is attributable to source-rich people have water piped into their houses whereas the poor must buy water sachets and other small units. The poor may spend most of their day in the pursuit of activities to acquire water. These people are consuming very close the floor of water required for survival. Therefore, as the per capita consumption drops near the floor, the price premium for water goes up. A reduction in population was included for model integrity. It is particularly associated with an increased pressure to leave the city and so Relative Water Availability was formulated as having an effect on population. The elasticity used in that formulation was very shallow and the slope was non-zero only after a threshold: a reduction in availability by more than 50% since the literature suggests that it is not a loop often in operation.

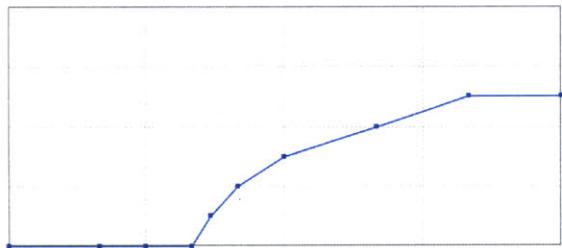
⁵Studies have found that disenfranchised people in mega-cities may (or must) pay 10 times more for their water than the very rich[67, 34]



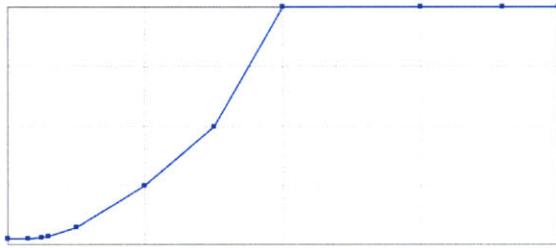
(a) Elasticity of Household Reduction to Availability



(b) Elasticity of Household Water Intensity Growth to Availability



(c) Elasticity of Reduction in Household Consumption to Budget



(d) Elasticity of Household Budget to Proximity to Floor

Figure 3-17: Formulations of table functions for calculating average household water intensity. The values for these graphs are also given in the equation listing in the appendix.

Domestic Demand is sensitive to population growth, average household size, and the average household water intensity. Population Growth and Average Household Size are considered exogenously, so the calibration focused primarily on calibrating average household water intensity, which was done through the sensitivities of feedback loops pertaining to average household water intensity to the elasticities, thresholds, and time constants. The elasticities are estimated from intuitive assessment of the likely response of decisions about household water use to pressure from availability and affordability as described in the equation listings and are depicted graphically in Figure 3-17. The relative magnitudes of each of the elasticities and steepnesses of slopes were estimated and examined through sensitivity behaviors.

The calibration of domestic demand seems to replicate endogenously the oscillations associated with historical household demand in Singapore. There is quite a bit of overlap in some of the elasticity sensitivities and the calibration of these variables is an indeterminate solution. In other words, there seems to be more than one combination of elasticity formulations and time constant values that recreate historical household behavior. Since Singapore has

often operated within a relatively stable regime, the formulations under extreme situations is likely to not be robust. There is also a question of whether the elasticities and thresholds are the same between cities or different. This would be an important consideration in developing typologies from application of this model and might be a useful point of comparison.

Economic Activity and Nondomestic Water Demand

Water that is not consumed domestically is aggregated into nondomestic Demand. Non-domestic demand therefore includes everything from water used for irrigation in municipal parks to water used for production of silicon wafers. Contrary to domestic water demand, which was normalized by households, it would be less meaningful to normalize nondomestic water demand by the number of businesses because the variation in size of businesses and the services for which they use water may drastically differ. For instance, not only is a silicon wafer plant or electricity plant likely to use many orders of magnitude more water than a bookshop, but differences in company size, such as the of number of employees, operating costs, and revenue would make comparison difficult. The normalized nondomestic water demand is formulated as an average economic water intensity, a relationship formulated in Equation 3.14. The economic productivity of the economy relative to population is a relatively meaningful measure of affluence in a city, and so the efficiency of the economy at converting an input of water into a financially valuable output is considered instead. Using this metric provides a future basis for disaggregation of types of industry, and comparison of water demand relative to contribution to societal value.

Total water demand in the nondomestic sector was found to increase but shows signs of leveling off; the average water intensity of economy (total nondomestic water demand per unit of economic productiv) has decreased. Nondomestic water demand is formulated as:

$$Demand_{Economic} = Intensity_{Economy} * Size_{Economy} \quad (3.14)$$

Examining the reference behavior of the size of the economy and economic activity give insight into the behavior of normalized economic demand, i.e. water intensity.

Economic Growth

The economy of Singapore has changed in both character and size. The economy of Singapore has seen rapid exponential growth that is surprisingly smooth for the past half-century despite turmoil in regional and international economies, as observed in Figure [singaporeecon](#). Inflows and outflows to economic capital are both proportional to the size of economic capital at any given time[21], and since the economy has inertia it is formulated in the model as a stock. Both the gross fixed capital (GFC, Economic Capital in the model) and economic activity (GDP, productivity in the model) have increased over the past 50 years. The materials required for industry also follow an exponential growth pattern as seen in Figure 2-2.

When water demand is normalized by economic activity, it is observed that the water efficiency increases over time, as observed in Figure 3-19. This pattern has also been observed in material requirements as observed in Figure 2-6 and has also been documented for other economies[93, 94]. The decrease suggests an exponential decay, suggesting that the feedback loops which decrease water intensity dominate the reference mode behavior and that there is at least one reinforcing loop driving the decline. Since the water intensity of economy depends on the type of industry and the technology in use, it has an inertia and is modeled as a stock.

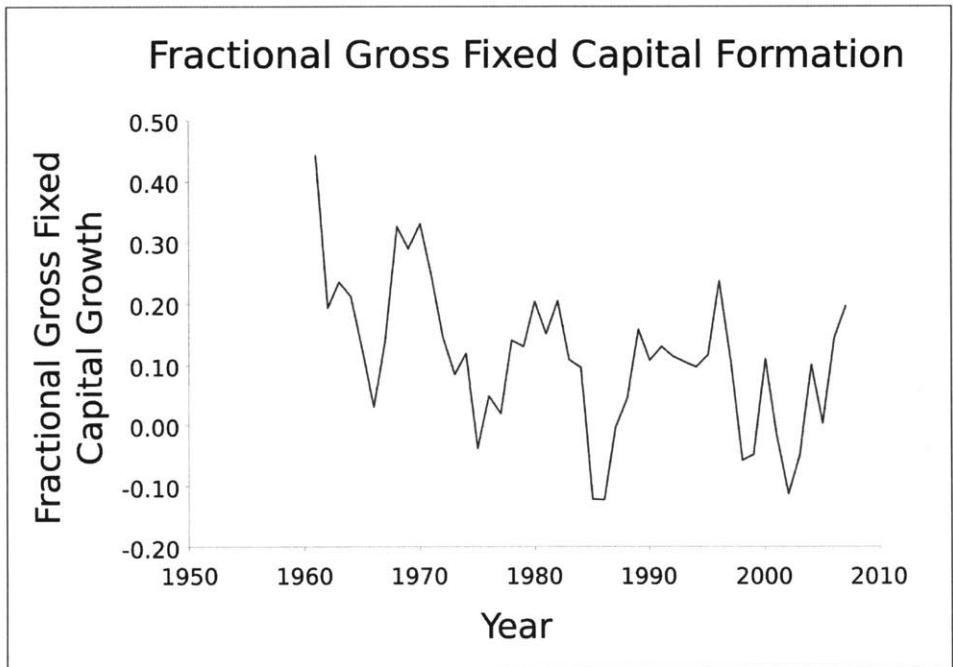
The economic intensity of water decreases in Singapore over the past 50 years, a process that has been observed elsewhere and termed *dewatering*[93]. The main behavior operating with regards to Economic Water Intensity is a reinforcing loop acting to bring the average water intensity down towards zero and is a business efficiency or technology-driven process. This decay is limited by the stock of economic water intensity itself; as the stock gets smaller, there is less to reduce and it is harder to make more reductions. At any given time there is likely a theoretical minimum to economic water intensity that depends on the technology and business practices at that time. The time to reduce demand is considered to be on the order of the time to reduce domestic demand since it is uncertain whether there is more or

less inertia in water demand from the economy than to domestic water demand. The overall model formulation is depicted in the model view in Figure 3-10.

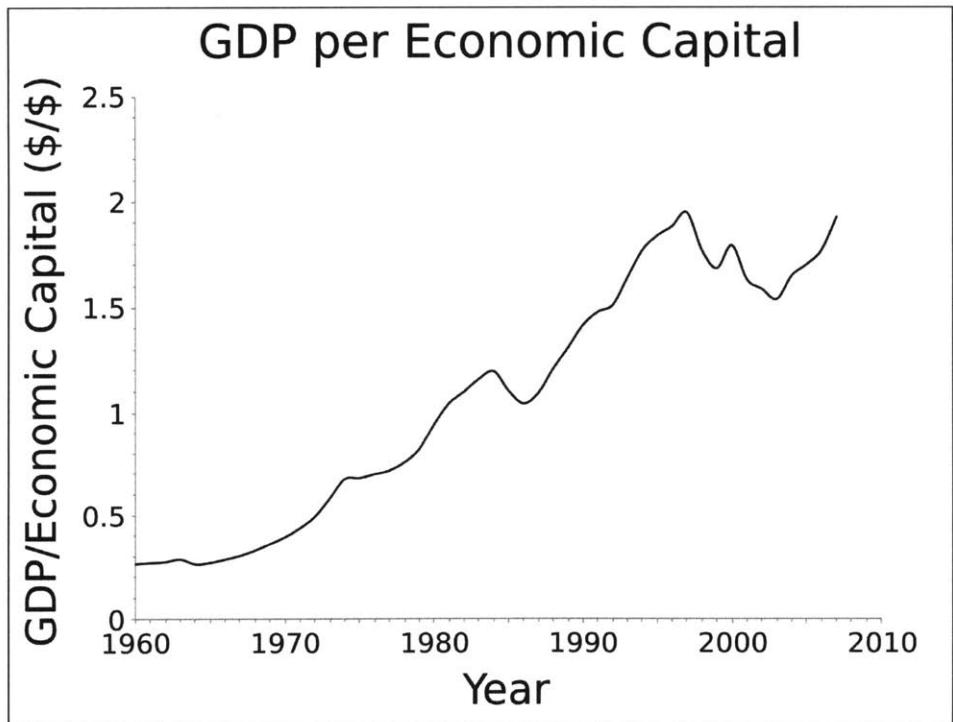
The historical reduction in Economic Water Intensity appears to undergo two different transitions, as observed in Figure 3-19. The first transition occurs over the period from 1960-1975 and appears to be a steeper reduction than what occurs after that. That is perhaps partly because of the transition from less economically productive, more water intensive industries to more economically productive, higher water intensity industries.

Historically, the reductions in economic intensity coincided with changes in the type of industry that dominated the economy. These changes in the character of the economy are observed in the changing land use depicted in Figure 2-3. Although by 1950 the economy did not depend strongly on agriculture, nevertheless there was much more agricultural land in use at that time. Agriculture is one of the largest consumers of nondomestic water and produces a product of relatively low economic value, so any transition away from an agriculture typically achieves a drastic reduction in the water intensity of the economy, a transition that has also been observed in Canada[94]. In addition to a reduction in water demand due to declining agriculture, there was also a marked shift away from water-intensive industries, a process which was likely both driven by policy makers and driven by economic development[20, 94]. In particular, in the early 1980s the government sought to actively promote economic growth in industries that had a high economic output to water ratio and to discourage and phase out industries with high water intensities relative to economic output[20]. Some of the industries that grew during this time produced products of high economic value (such as silicon wafers), but also required large freshwater inputs. Those remaining industries comprise the primary market for most desalinated and reclaimed water produced. However, economic activity in Singapore continues to progress towards more service-based industries[20].

The reduction in economic water intensity is associated with the transition in character of the economy. Although the economic water intensity in this model was not explicitly linked to the type of economic activity or described endogenously, environmental impact has been endogenously formulated in other System Dynamics models to examine the links between urban



(a) Rates of formation of economic capital.



(b) Productivity of economic capital

Figure 3-18: Variables pertaining to economic activity in Singapore, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

metabolism and the local environment. The Cobb-Douglas function was used by Güneralp and Seto to endogenously model the economic transition through primary (agricultural), secondary (manufacturing and other material-heavy industries), and tertiary (service-based industries requiring low material input) economies in their investigation of urban metabolism and environmental pollution in Shenzhen, China[39].

In addition to a transition away from relatively water-intense industries, another impor-

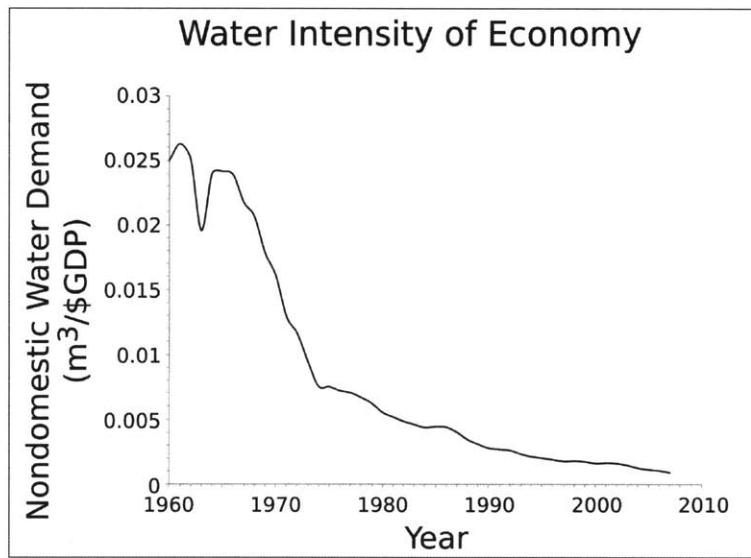


Figure 3-19: Water Intensity of Economy was calibrated with reference to the historical behavior. Notice a steep declining slope up to 1975 and then a shallower slope after that, which is likely related to the policy of encouraging companies with a high economic value per unit water used to replace less water-efficient industries in the economy[20].

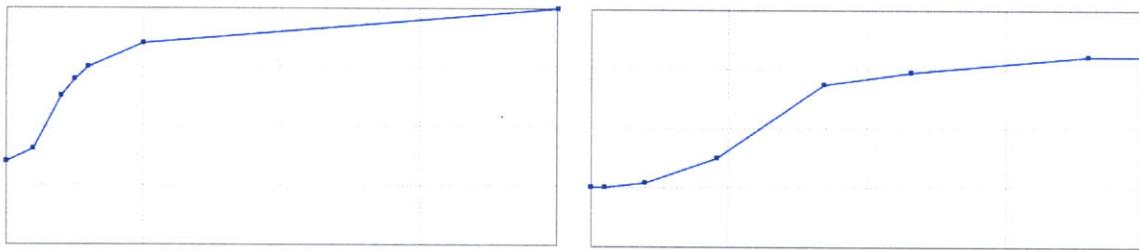
tant process leading towards reduced water intensity is the reduction driven by process- and technology-based improvements within a particular industry. At any given time there will be a theoretical limit to the reductions in water intensity can be achieved. These theoretical limits depend on the physical stock of infrastructure and the theoretical water efficiencies that can be achieved there, the delays associated with improvements in physical things. Overall, improvements in technology and changes in the type of industry lower this theoretical ceiling for water efficiency and the achievable floor of economic water intensity over time down over time[94]. These improvements are driven by a constant pressure from management to improve profits and gives rise to a constant reduction in water intensity. The constant pressure likely arises from a floating goal in management to continue achieving reductions in water

intensity, which is a reinforcing loop[21]. The mental models and technological inertia were not modeled explicitly and are instead aggregated into the parameters used to calculate possible and normal reduciton in economic water intensity.

For the sake of completeness, a reinforcing loop that driving growth of the average water intensity of the economy has been included. The process motivating the inclusion of this loop is, similar to the formulation for domestic water demand, the 2nd law of thermodynamics. All other things being equal, water demand is likely to increase over time due to the accumulation of inefficiencies and infrastructure deterioration. This loop could potentially drive the business improvement reinforcing loop in the opposite direction such that the average economic water intensity increased over time.

The primary driver of average economic (nondomestic) water intensity is economic activity, which is an exogenous process in this model. The nondomestic demand historically depends on the pace of economic growth relative to reductions in the water intensity of economic activity. The calibration of this reduction was approached through calibration of variables pertaining to the reduction over time. This reduction is exogenously generated relative to other variables in the model as shown in the model results for scenario , in which the average economic water intensity is the same for all scenario runs that do not explicitly adjust the parameters determining economic water consumption. This is in part because the actual decision making processes driving change in average economic water intensity are not well known. It therefore seems more accurate and useful to allows the relative trend to be estimated and input rather than having the model generate the dynamic endogenously. These processes are modeled as exogenous parameters and non-linear, elasticity functions such as those depicted in Figure 3-20.

The calibration of these variables was achieved through sensitivity since for the most part these are theoretical variables. Calibrating the growth in economic water intensity was challenging since reductions in water intensity dominated historical behavior. The calibration of growth in economic water intensity would benefit from information about business perfor-



(a) Elasticity of Pressure to Reduce Economic Water Intensity to Water Intensity (b) Elasticity of Household Water Intensity Growth to Availability

Figure 3-20: Formulations of elasticities of economic demand to affordability and availability. The values are also given in the equation listing in the appendix.

mance data and conversations with people in industry.

Average economic water intensity is particularly sensitive to the Elasticity of Economic Water Intensity to Pressure to Reduce and to the Elasticity of Pressure to Reduce Economic Water Intensity to Water Intensity. The slope of the trend is strongly determined by the Normal Desired Reduction. The Normal Desired Reduction is a model approximation of a business decision-making process to increase business performance each business cycle. The Time to Adjust Water Intensity affects both the slope and especially how quickly the trend approaches the Minimum Achievable Water Intensity over time.

Similarly to the calibration of average household water intensity, formulations of elasticities and the values of thresholds and normal values for average economic water intensity were calibrated through sensitivity testing. Although this dynamic formulation seems to capture the dominant feedback processes observed in the data, because decision making feedbacks were not explicitly based on information from business managers the results and dynamic behavior should be considered with reserve. However, the current formulation does recreate the historical trends, and if nothing else it provides a dynamic model input that allows decision makers to see graphically how the relative trend in average economic water intensity impact overall socioeconomic demand and water availability and could be useful as a platform for policy making.

Population and Economic Activity

Both population and economic growth has contributed to increasing demand for water over the observed time period. Population and Economic Capital are both associated with exponential growth. Population and economy are not separable; population growth gives rise to economic growth and vice versa. At any given time, the economic productivity of economic capital should depend on the population. If there are no people in the city, even if the economic capital in the city is high there should not be much economic activity relative to what it would be otherwise. Economic productivity also depends on levels of education and other socially endogenous variables that are highly pertinent to material consumption. Therefore, although an understanding of the social and cultural processes that has given rise to the particular economic growth patterns in Singapore, the economic productivity per person was formulated using the Cobb-Douglas function[95]. This formulation was also included to facilitate the internal model adjustments to economic growth such that the population can be reasonable modeled by calibrating average fractional population growth and decay factors instead of exogenous data input. The model formulation of the interactions between population and economy are depicted in the model view in Figure 3-21.

Population interacts with the economy through employment. In order for economic capital to be productive, labor must be employed. The relative economic value produced by each laborer depends on the type of economy and the level of education achieved by the workers. In addition, the type of economy that can be supported also depends on the relative level of education. The contribution of education to economic productivity is formulated by the Cobb-Douglas function. Güneralp and Seto[39] applied the Cobb-Douglas function to a System Dynamics model of Shenzhen, China, and it is also used here, though considered exogenously.

The workforce supported at any time was considered relatively exogenously. The employed workforce (determined from statistics on unemployment and population) was graphed against economic capital, and also the employed workforce relative to economic capital was plotted over time (see Figure 3-22). From this information, an unemployment rate was determined.

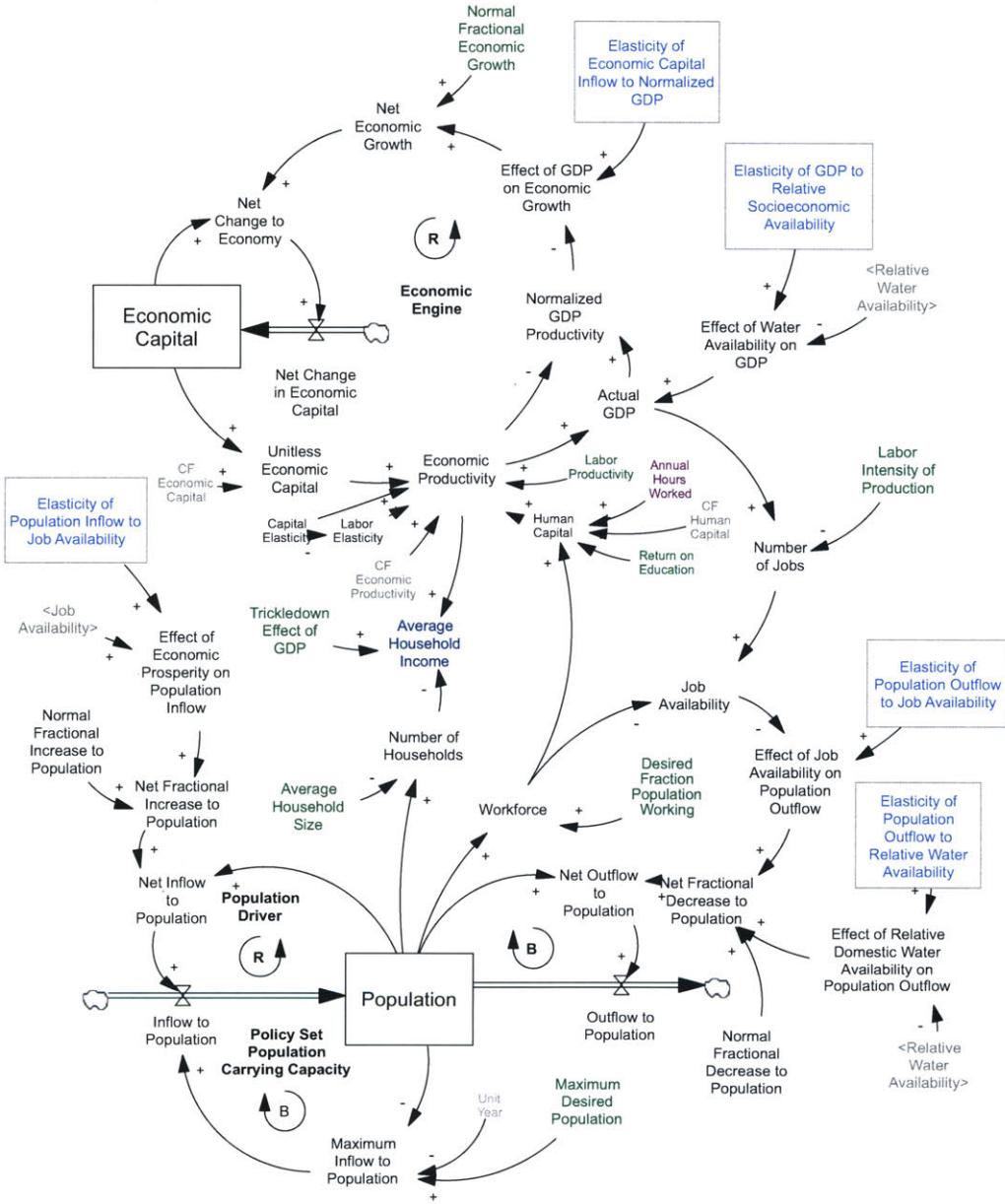


Figure 3-21: Figure showing the model structure for population and economy

If unemployment increases greater than it is otherwise, then the population outflow increases and the inflow decreases relative to what it would be otherwise. The effect of unemployment on population inflow and outflow are formulated as table functions.

Although historically unemployment has not dropped below zero, theoretically it is conceivable that there are more jobs than there are people to fill them. To provide model robustness, the model was formulated to deal with this situation. If the number of jobs rises above the number of workers, then there is an incentive for people to move into the city but economic productivity suffers. The model is formulated such that if economic productivity suffers, then the outflow to economic capital increases.

Water Resources Limit Socioeconomic Demand through Relative Water Availability Ultimately, the amount of water that can be consumed at any given depends will depend on the water that is available, so water consumption is a variable that adjusts instantaneously. However, *demand* for water does not change instantaneously. Therefore consumption is disaggregated relative to demand. Relative Water Availability determines is a variable that determines how much water can be consumed at any one time and is defined as the amount of water that can be supplied to the socioeconomic system relative to the total demand:

$$\text{Relative Water Availability} = \frac{\text{Maximum Outflow to Water Resources}}{\text{Total Socioeconomic Demand}} \quad (3.15)$$

Availability is a measure of how much water this is relative to demand. As availability goes down, there are two potential ways in which the water availability could be brought back to a target availability: either socioeconomic demand could be brought down or the water stock could be brought up. If water availability is less than demand, then there is a shortfall in the current supply. When the shortfall in the current supply is greater than zero, there will be both a pressure to reduce demand and a pressure to increase the water supply.

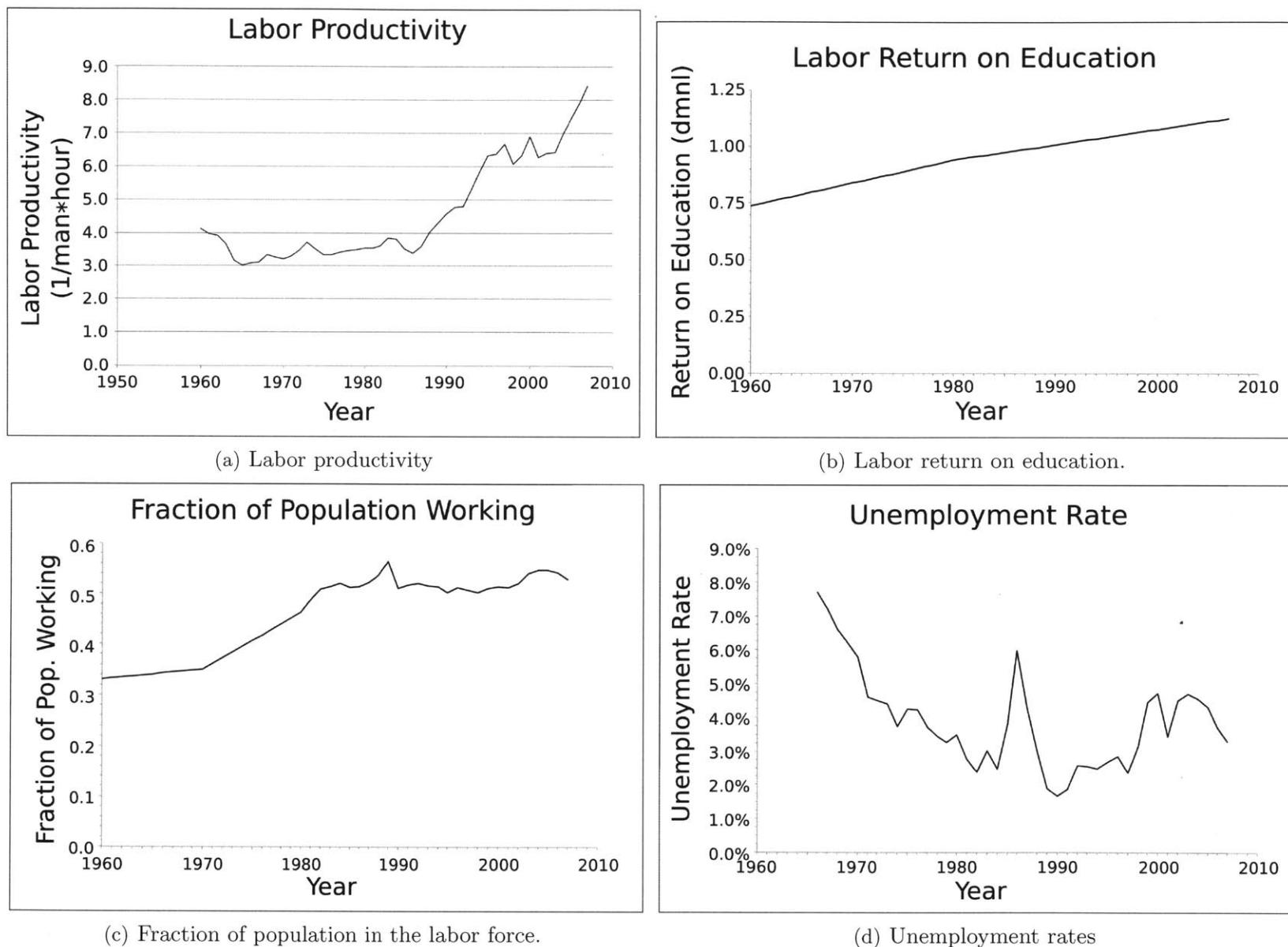


Figure 3-22: Historical values of factors pertaining to the productivity and size of the work force and percentage unemployment in Singapore, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

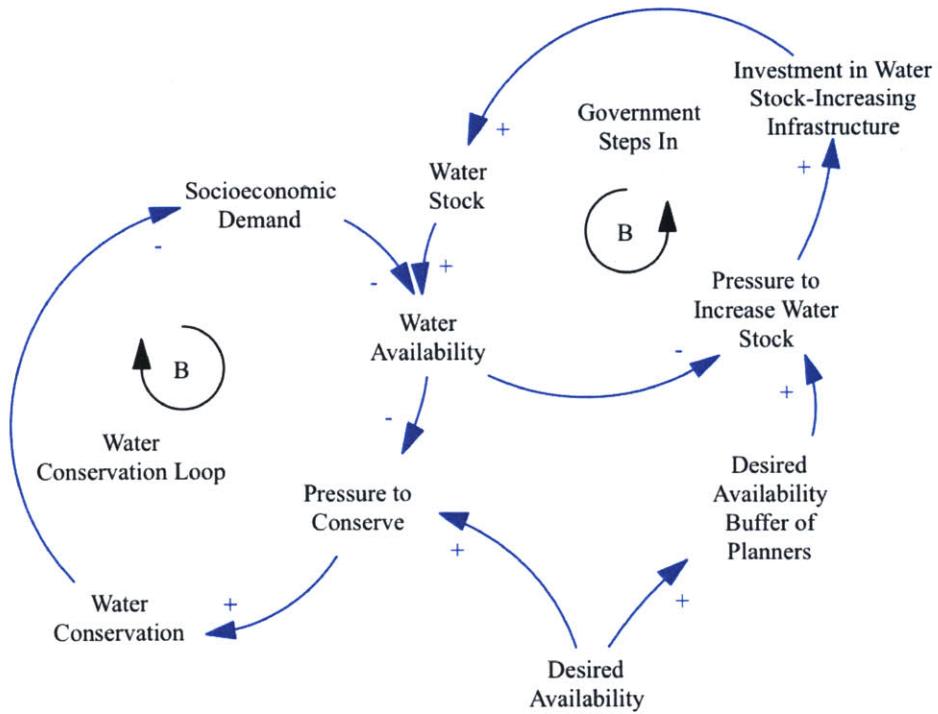


Figure 3-23: Causal loop diagram conceptualizing the balancing loops important to determining availability.

Relative Water Availability is only defined on the interval $(0,1)$. If Water Resources are much higher than demand, then the relative water availability is considered to be equal to one. As demand goes up, consumption goes up relative to what it would be otherwise, and as consumption goes up, water resources go down. As water resources go down, water availability goes down, and when water resources fall far enough, water resources will not be enough to meet demand and socioeconomic consumption will be limited by available resources.

If water availability drops by a significant amount, very quickly, the normalized shortfall between consumption and demand will be high, which will have an effect on outflow from population and economy. People will leave; the economy will suffer. the elasticity of these outflows to water availability depend on how much the water availability affects domestic survival and economic productivity. If water availability drops below the floor of water consumption required for households then there will be a higher outflow from population than there would be otherwise. Historically, there is not much indication that this was *not* an im-

portant reference mode in Singapore's water history. However, because the model deals with time scales on the order of decades and centuries, that a water crisis involving a long-term reduction in water availability is conceivable. If such an event were to occur, as much of the shortfall as possible would be taken up by reductions in demand and unusual water economies arising from the higher water prices possible. But it is conceivable that the shortfall would be so catastrophic that the population outflow would be significant.

If water availability dropped low enough to approach the absolute floor of per capita water consumption, then the outflow to population might increase not only due to emigration, but also due to mortality (emigration and mortality are aggregated as a net fractional population decay factor in this model). Mortality arising from low water consumption and water quality is most likely to affect those with compromised, sensitive, or otherwise vulnerable immune systems such as the very young and very old[67], which would change the average age of population and incur other changes in the socioeconomic system such as changes economic productivity. These affects are outside the bounds of the model, and so they have been considered exogenous. The approximation of the effect of urban system behavior to water scarcity as exogenous of these variables is supported by studies indicating that the relative economic vitality of an urban area is more likely to determine net population growth than water quality, a dynamic observed in modern mega-cities such as Manila, the Philippines, and Mumbai, India[33]. To summarize, limited water availability will mainly increase the household conservation of water and reduce household demand. As the floor of consumption for domestic water is reached, the acceptable price for water will increase. That will give rise to more resources to expand water supply through non-conventional means.

Economic activity is more likely to be sensitive to an increase in economic pressure from water price than to availability. It is also conceivable that the relative water availability dropped low enough that economic productivity would suffer. Economic productivity would likely not be affected as soon as relative water availability dropped below one. There would be some capacity for production to continue with reduce water supplies, a flexibility that would probably depend on the industry as well as relative profligacy in use. The formulation

of this type of scenario was not explored with this model.

A shortfall in relative water availability relative to demand was formulated to affect the economic water intensity, similar to the formulation for domestic demand. A reduction in availability or affordability both create additional pressure to reduce water intensity. The sensitivity of economic activity to these variables was formulated with balancing loops as described above. The management structure and decision variables driving the feedbacks for economic water intensity are at this stage more symbolic and aggregated, as described below and are therefore only so meaningful. However, it is hoped that since the modeling structures below do depict the reference mode behavior of economic water intensity, that for the time being they will be moderately useful and provide a basic dynamic unit for future examination and analysis. Suggested improvements would be to identify more explicitly the decision structures providing feedback and between economic activity and water demand.

3.3.4 Water Supply Management through Government Intervention

All other things being equal, availability will ultimately limit socioeconomic demand. The causal loop structure describing the dynamic hypothesis for these feedbacks between water availability and management is depicted in Figure 3-24. If socioeconomic demand is allowed to arise such that this loop does operate, water availability (and consumption) may oscillate as both demand and water resources are stocks involving time lags. The response of government to that potential system behavior is formulated to account for two different types of policies. The first policy approach is supply management, or the increase in supplies in order to provide a supply sufficient to meet demand. The second policy approach is demand management. This policy approach requires the application of artificial policy pressures to gently reduce demand such that demand does not overshoot supply.

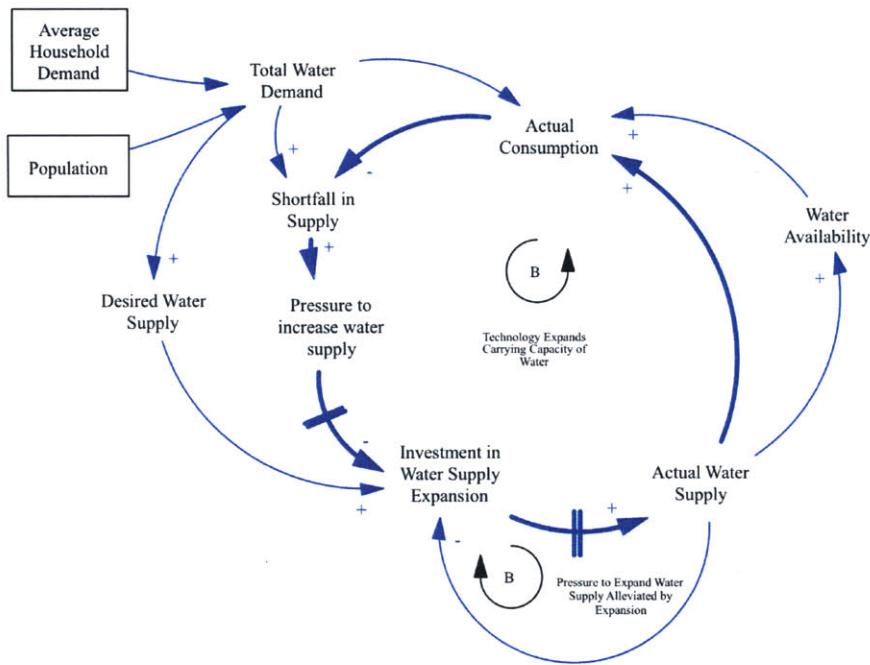


Figure 3-24: Causal loop diagram capturing supply and demand processes.

Supply Management

Supply management is an important water policy that requires the identification of current or future shortfall and the planning and construction of infrastructure to increase demand beyond what it would be otherwise. If water resources are insufficient to meet demand, in addition to reducing consumption and creating pressure to conserve water and reduce demand, the shortfall also puts pressure on the government to expand water resources. However, the government cannot increase the water supply instantaneously. Expanding water supply requires expanding infrastructure, which takes years to plan, design, finance, and build. Governments that wait until demand outpaces supply before expanding infrastructure will govern unstable cities. Since the provision of socioeconomic stability and reduced vulnerability to natural disasters is one of the chief mandates for establishing government, system instability is not a desirable operating mode. To achieve smoother system behavior decision makers must take into account the time it takes to plan, construct, and finance infrastructure expansion and project supply and demand into the future, and assess whether trends

suggest a future shortfall and if so, may increase infrastructure such that water resources do not fall below demand[21]. That Singapore's successful water management is attributable to thoughtful management and planning is the dynamic hypothesis proposed by decision makers within the system itself[20] as well as external water systems experts like Tortajada[35].

The policy making structure with regards to calculating demand relative to supply is formulated in the model as follows. Decision makers are assumed to base their decisions on projected socioeconomic demand. These projections are based on historical trends in domestic water demand and nondomestic water demand. In the current model, decision makers are assumed to calculate exponential trends and not just linear trends. The trend that is used in projections should reflect the actual process used by decision makers. For Singapore, it was uncertain what type of calculation was used but it is not unreasonable that they should use an exponential growth model.

The projected shortfall in trend that is calculated depends on the interval over which the trend is formulated as well as projection into the future. The trend is more likely to be accurate the longer the interval used to formulate the trend, especially relative to the projection time. For instance, if a 2-year trend is used to calculate demand 50 years into the future, the projected demand is less likely to be accurate than a 2-year trend used to calculate demand 2 years into the future or a 25-year trend used to project 30 years into the future.

Future iterations of the model might benefit from disaggregating domestic demand into trends in population and per capita or household demand and to disaggregate nondomestic demand into economic size and growth as well as economic water intensity. Future iterations could also include a model feedback so that if there was a current, rather than a future, water shortfall, the pressure to increase water supply might alter system behavior. However, the likely operating mode resulting from that would be similar to what would happen in this model if the duration and forecast horizon used for calculating demand were set to some small number, such as a fraction of a year.

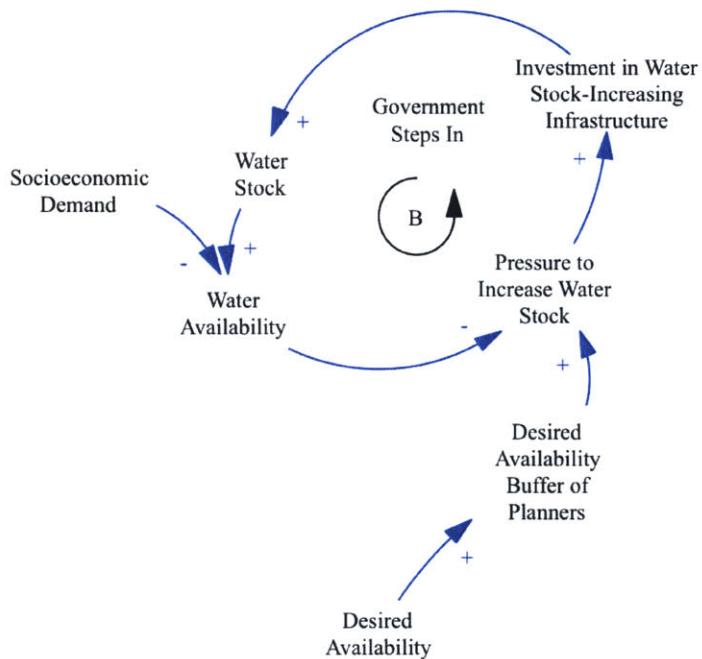


Figure 3-25: Causal loop diagram of the feedback between water availability and infrastructure expansion.

Infrastructure Expansion

When a shortfall in water supply relative to demand is identified, there will be a desired increase in water infrastructure capacity. Infrastructure capacity is formulated as a yearly volumetric flow, in units of m^3/year . The actual infrastructure order rate will depend not only on the projected need, but also on the cost of the projected infrastructure. The water utility has finite financial resources, and while the utility could potentially take out loans to finance water infrastructure expansion, even loans are a limited financial resource.

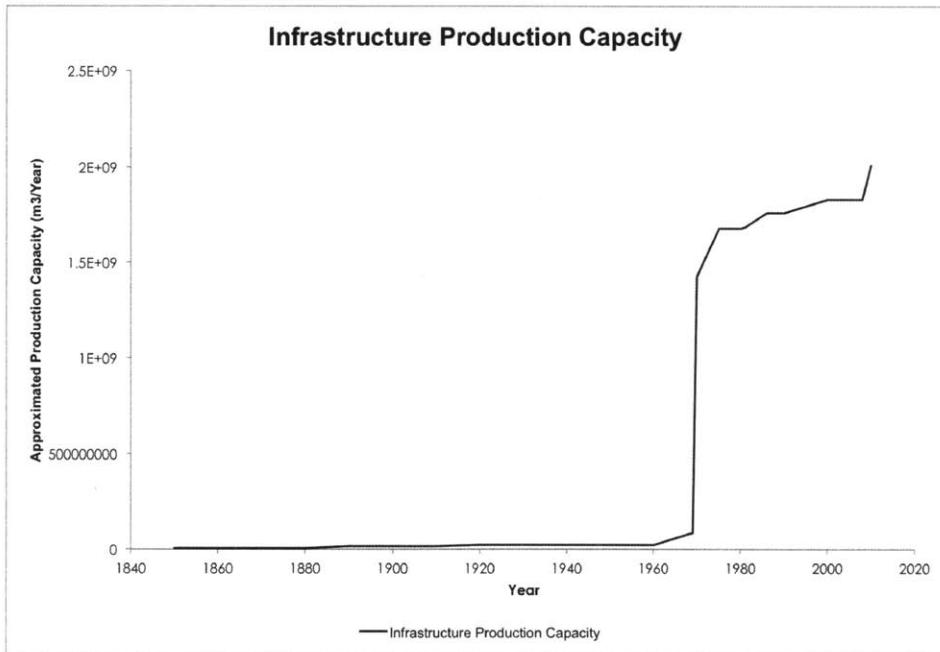
Whether PUB has enough financial resources to fund a particular expansion of infrastructure depend at any time on the stock of financial resources that PUB has, relative to other costs that might need money more than infrastructure expansion. Other processes that require money from PUB include the cost of overhead for operation and water production and maintenance of current infrastructure. If the financial resources required by operation, maintenance, and expansion exceed the financial resources that PUB actually has access to,

financial resources are not assumed to be distributed evenly between these needs. First, money is given to operating of existing infrastructure; then, financial resources are allocated for maintenance, and finally, money may be allotted for infrastructure expansion.

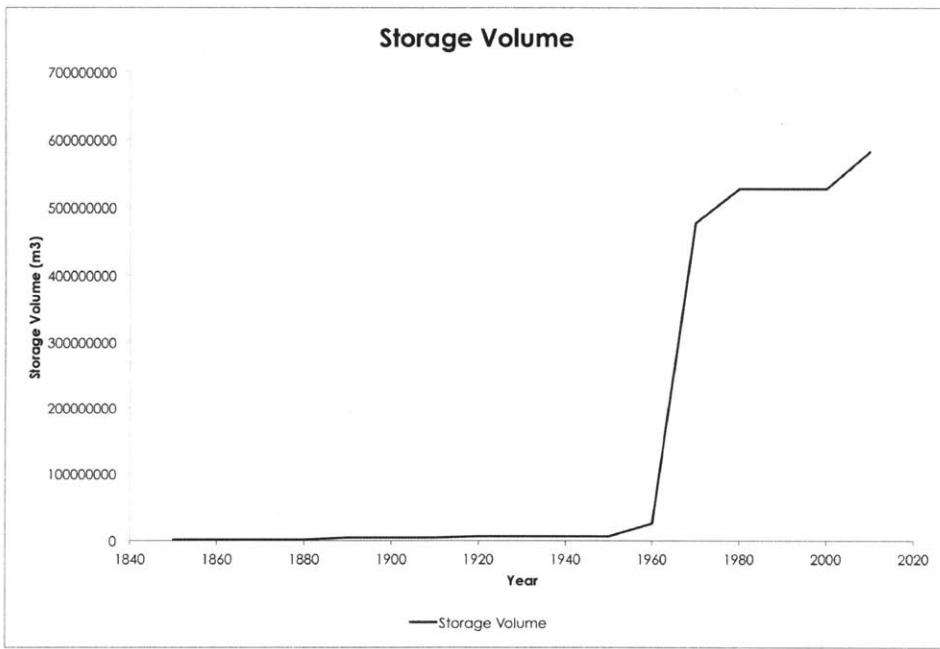
The formulation of allotment for infrastructure expansion is formulated such that if a shortfall in project resources is identified, more money is allotted for PUB in the next few years, if it is not already available. This increases the infrastructure on order. Infrastructure on order has to hang out in there for 15 years, because that is historically about how long it takes for PUB to identify that they want infrastructure and then get around to building it[20].

The model structure for water infrastructure and the management structure pertaining to its maintenance and expansion is depicted in Figure 3-27. Infrastructure was disaggregated into a series of stocks that depict whether or not management has identified a shortfall and ordered water infrastructure or not. If water infrastructure is ordered, there is a time delay associated with its planning and financing. When water infrastructure has been planned, it moves into a second stock representing Infrastructure Under Construction. The average time for construction seems to have remained relatively constant over the years, and is about four years as described in timeline in Section A.2.3, from PUB[20].

There is assumed to be a deterioration rate of infrastructure. There is a normal fractional rate of infrastructure deterioration. Since urban water infrastructure is complex and in the model is aggregated into a volumetric production capacity per unit time, this rate should be estimated by water system experts. It may become higher or lower depending on other factors, but is modeled here as exogenous. The model structure models deteriorated infrastructure as a residing in a stock that can flow back into Infrastructure Production Capacity. This represents deteriorated infrastructure that has undergone repairs. However, it might be more accurate to also include an outflow to Deteriorated Infrastructure that represented infrastructure that had deteriorated to the point that it was beyond repair.



(a) Infrastructure production capacity over time.



(b) Storage volume of reservoirs.

Figure 3-26: Parameters pertaining to infrastructure production capacity[20].

3.3.5 Carrying Capacity of Finances and Government to Investing in Technology to Overcome Natural Carrying Capacity

The government for an urban area can increase the resilience of the urban water system by planning ahead for the future. The government can increase the stock of water resources before availability of water drops below demand. The ability of a government to do this depends strongly on the resources a government has to build infrastructure as well as their capacity to predict demand. Changing the environmental carrying capacity through technology requires financial resources to develop and build that infrastructure[20].

In the early days of independence, the government of Singapore accepted two loans from the World Bank but quickly repaid these debts through conservative financial management of its utilities that prioritized cost recovery[35]. Water pricing structures did not subsidize the cost of water for affordability, instead being priced high enough to recover costs incurred during operation and maintainence of water infrastructure[35]. The historical data graphed in Figure 3-29(d) demonstrate the cost-recovery water pricing pursued by PUB.

Figure 3-30 depicts the historical change in water pricing for the domestic and nondomestic sector. The baseline price of water for domestic water was formulated as depicted in Figure 3-32 and came to include a penalty for water use above a baseline as depicted in Figure 3-30(b), which is formulated as a table function in the model in Figure 3-32. Historically, nondomestic water use was priced about twice as high as the baseline domestic water use, but now that total domestic demand for water has reached the level of consumption by the nondomestic sector this pricing gap has narrowed.

Setting the price of water to recover costs is modeled in the management structure for pricing, as seen in Figure 3-32. This has enabled the water utility to build its capital stock over time[35, 20]. Recently, PUB adjusted to cost of water to generate a surplus of funds in anticipation of future water costs. This surplus is managed by the central government but is modeled here as returning to PUB capital, as seen in Figure 3-28.

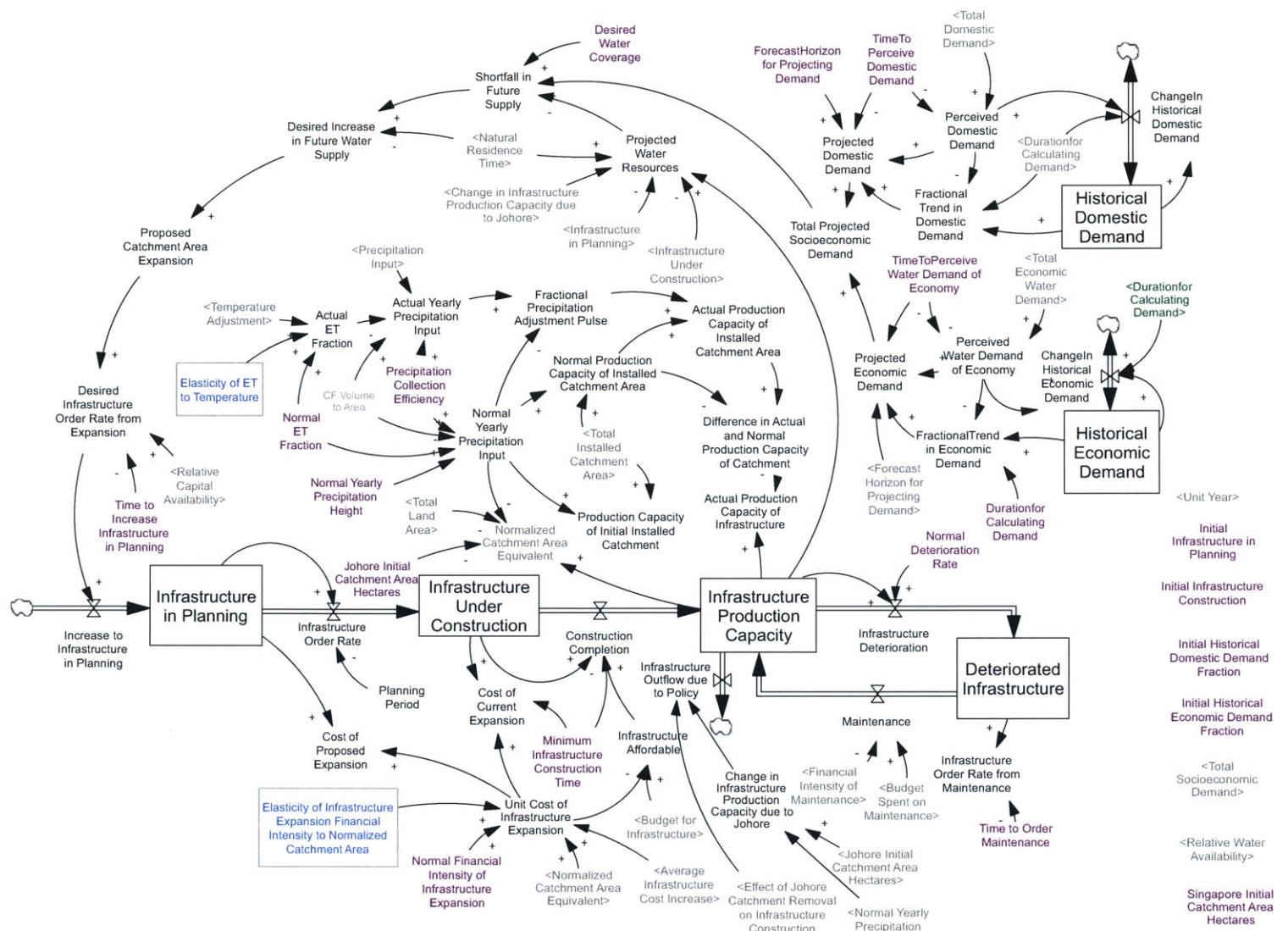


Figure 3-27: Figure showing the model structure for infrastructure production capacity

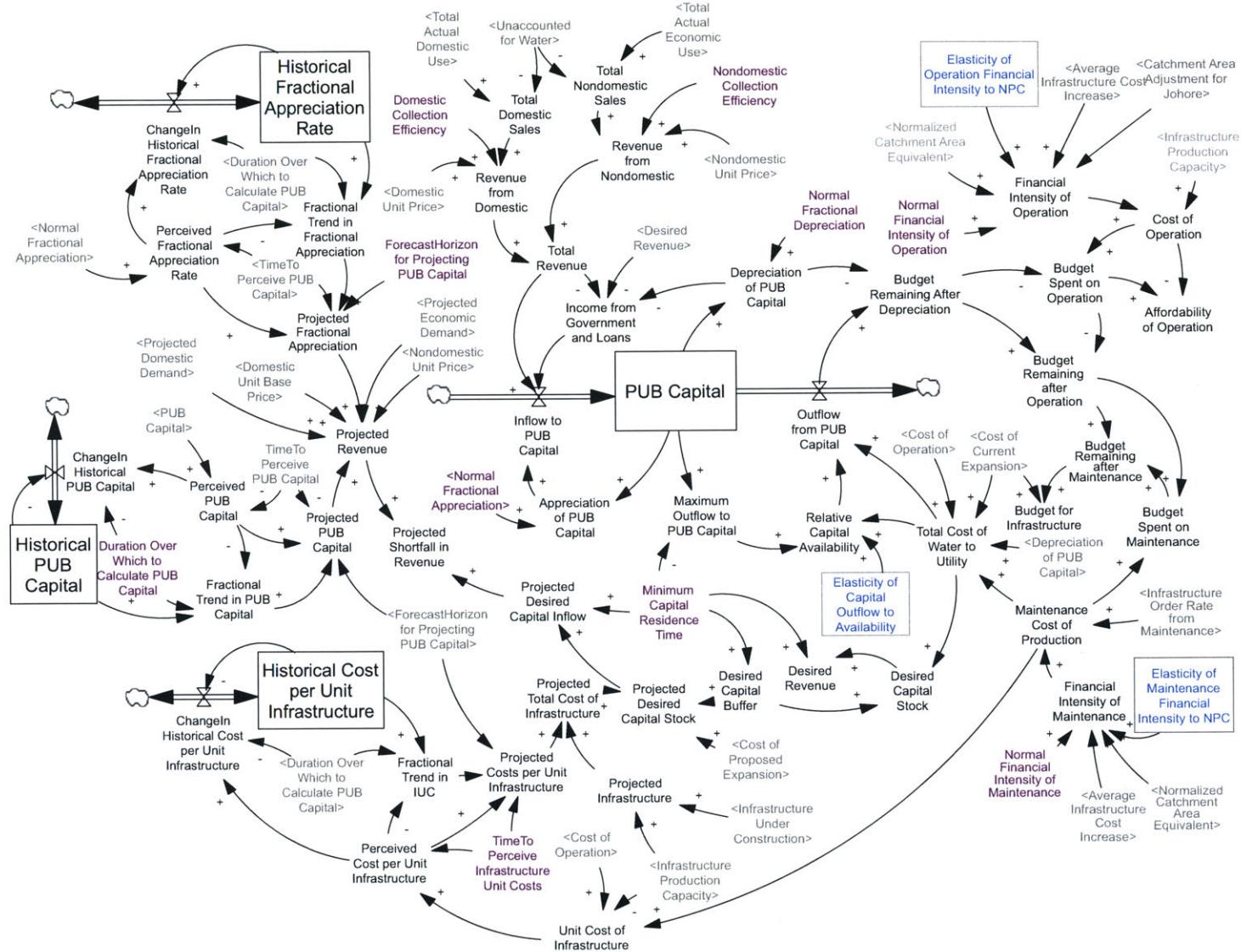


Figure 3-28: Figure showing the model structure for PUB financial resources

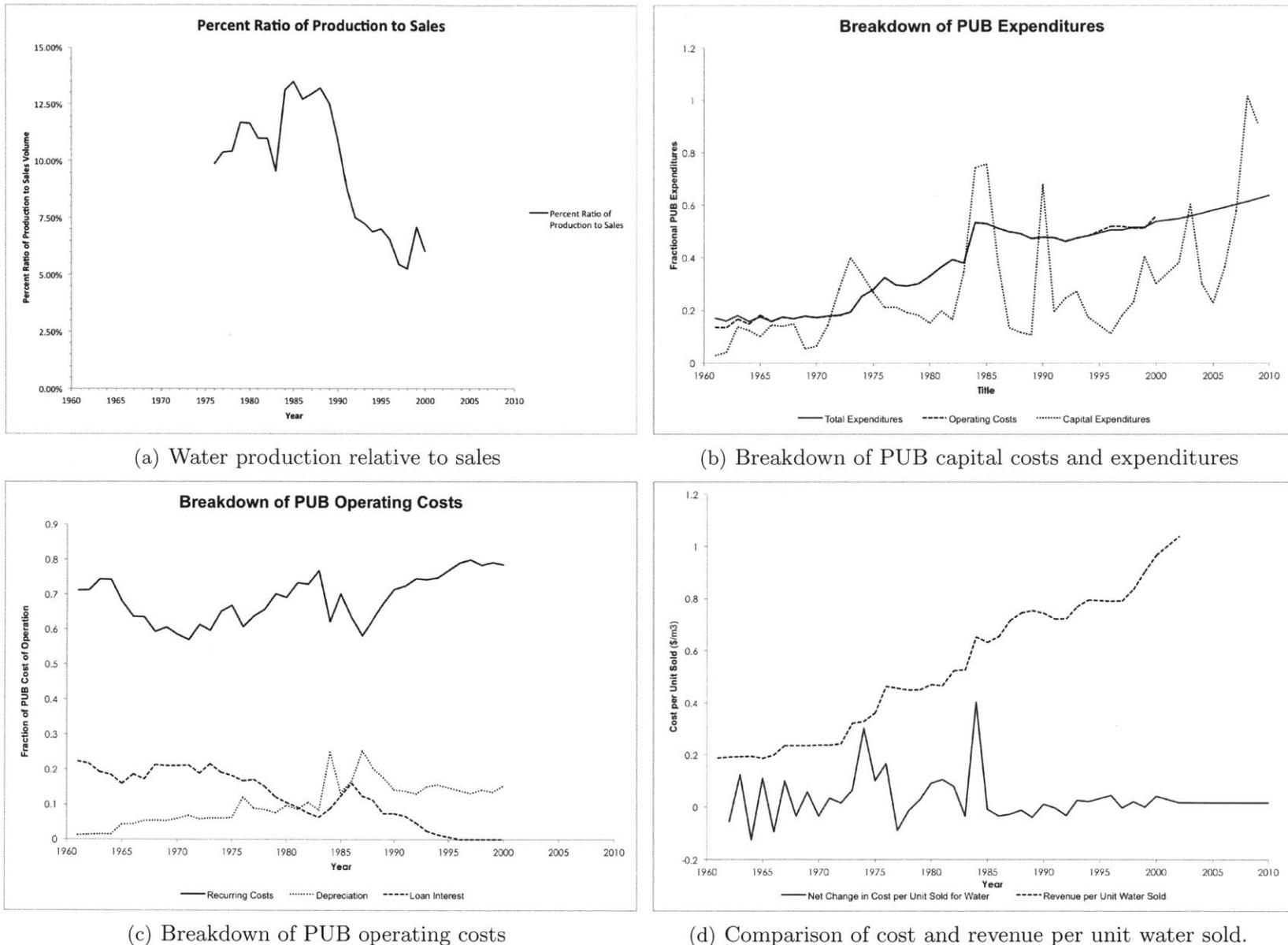
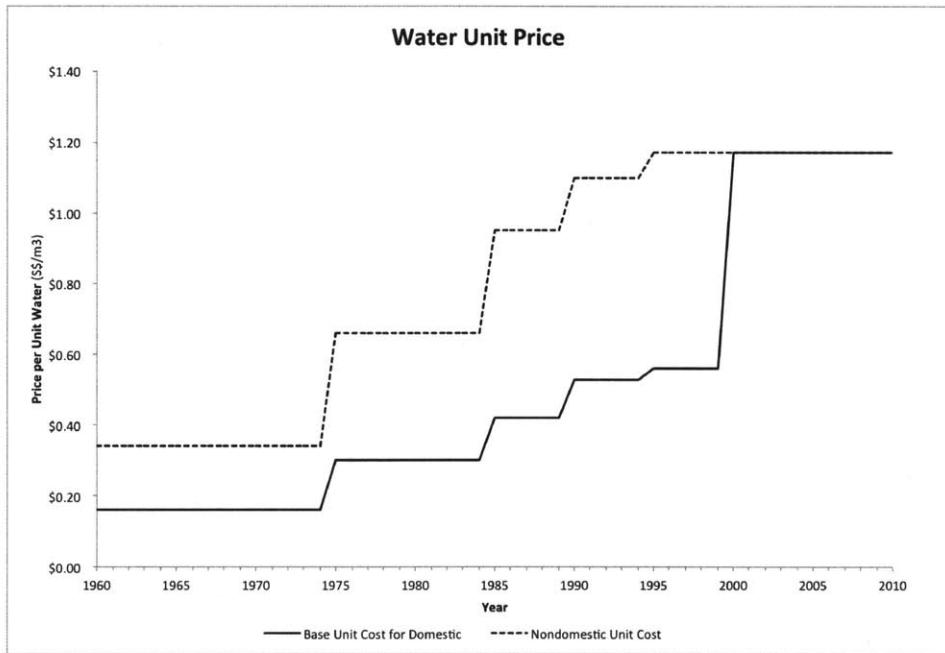
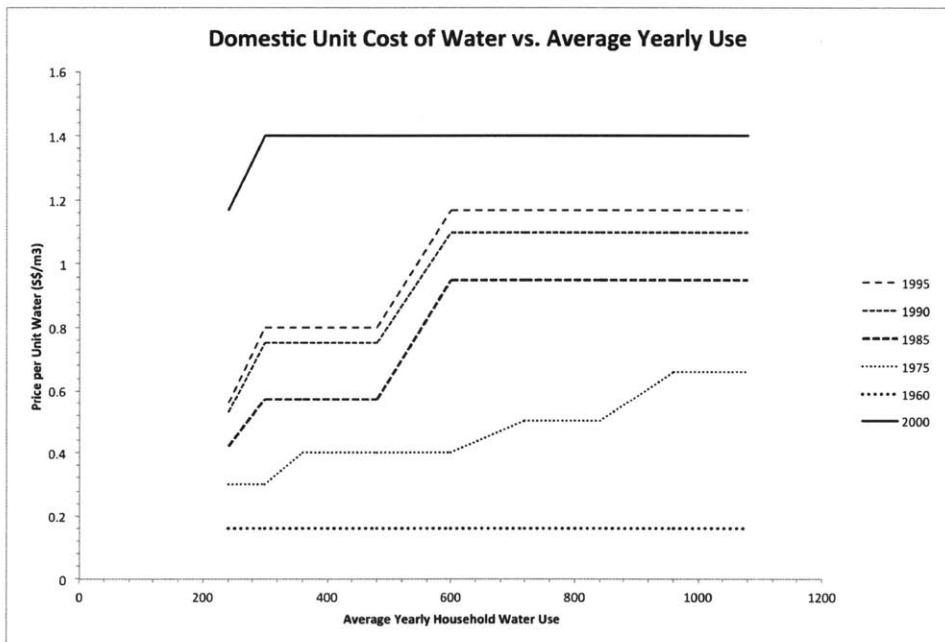


Figure 3-29: PUB data used in calibrating the financial intensities of infrastructure operation, maintenance, and expansion. The figures showing cost recovery statistics were used to calibrate the PUB management mental model, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].



(a) Unit price of water



(b) Financial penalty for above baseline use

Figure 3-30: Historical data pertaining to the unit price of water, and used to calibrate the model variables pertaining to pricing, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

Water prices also began to leverage a financial pressure that encourages water conservation. The Water Conservation Tax (WCT) was introduced to cover the costs of infrastructure operation and water production, offset future expansion costs, and reign in domestic consumption. In 1991 the Water Conservation Tax (WCT) was introduced to send a message to consumers that, when demand goes up and existing sources of supply run out, the next drop of water, or the marginal source, will come at a higher cost[20]. In 1997, a review decided to raise the tariff to account not only for production and supply but also in anticipation of future technological costs. The pricing structure was changed in 2000 to include other costs of infrastructure expansion as well as research and development, which had previously been funded by the central government. In 2000, the government adopted a new philosophy which regarded even the first drop of water as precious and at this time the potable water tariff was brought up to the non domestic water tariff[20]. This new philosophy required the WCT to apply to every drop of water rather than only being applied if consumption exceed 20m³/month.

The model assumes that building infrastructure requires certain resources in the form of labor, money, and raw materials, all of which require money. If the economic size is large enough and the finances are managed well, then water infrastructure can be expanded to finance increasing economic growth. If there is not enough money for infrastructure, then the capacity of infrastructure can be built will be limited. The causal loop diagram in Figure 3-31 depicts the decision making structure assumed in the development of this model.

The financial intensities of infrastructure were calibrated to historical data, as were pricing structures. The reference modes of financial intensities of infrastructure are depicted in Figure 3-30. Overall, PUB capital was roughly calibrated but since the data available on PUB capital over time is sparse, the main assumption used in calibration is that the time constants and buffers were conservative enough to grow PUB capital such that at no time historically did financial resources limit system operational capacity or expansion.

Depending on how big the required water infrastructure is, the more it will cost, and the less

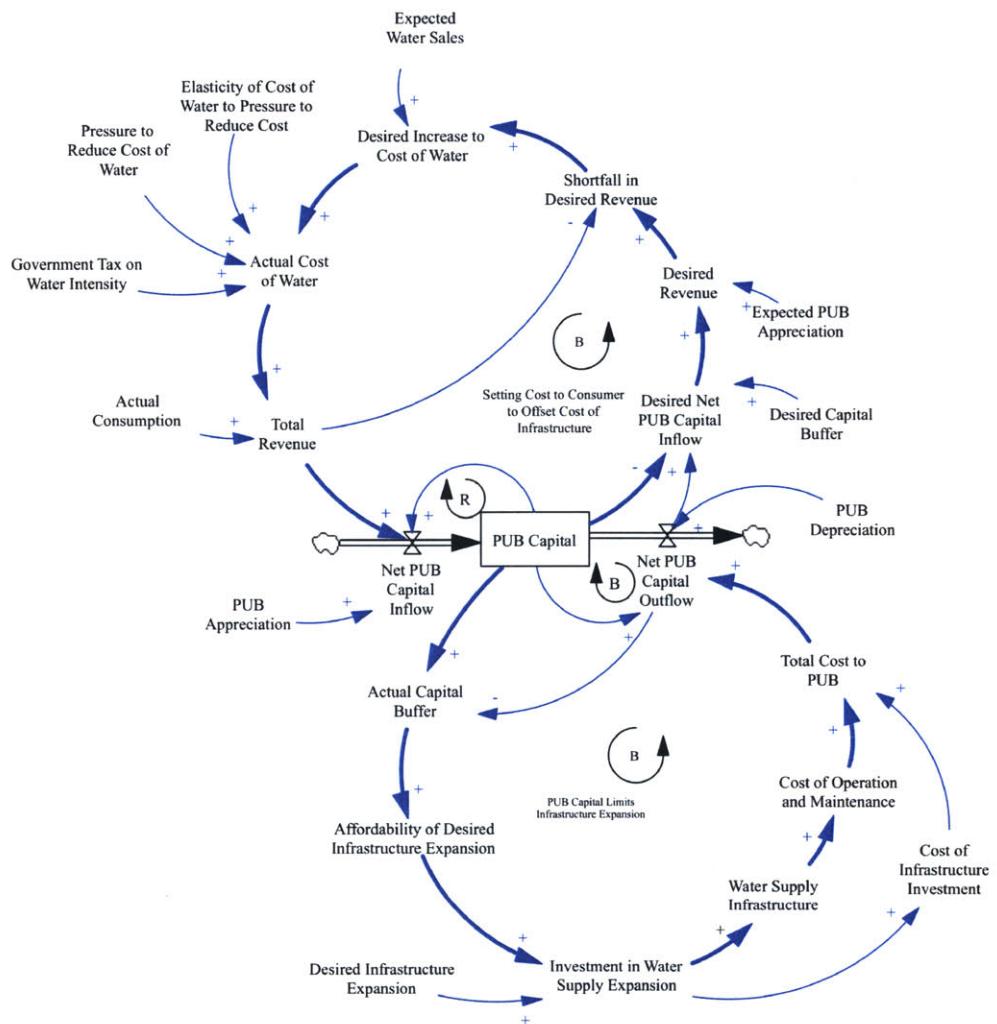


Figure 3-31: The carrying capacity of financial resources for infrastructure expansion.

affordable the infrastructure would be. The cost depends on the relative financial intensity of the infrastructure, which will be affected by the complexity of the infrastructure and its size. The complexity of the infrastructure is affected by the relative size of the infrastructure and the quality of the resource. If the freshwater is abundant, locally available, and relatively clean, then less infrastructure will be required. Financial intensity is an aggregate metric for relative complexity, which is a driver of material and energy intensity.

Capacity of Socioeconomic System, through Technology, to Overcome Natural Carrying Capacity

Given a certain level of technological resources (including, here, all knowledge and information available to the population), the socioeconomic system can overcome this carrying capacity, or raise it, through technology. This can be done by decreasing the per capita demand without decreasing the service associated with it (such as more water-efficient washing machines) and/or increasing the water resource itself.

The water resource may be increased many ways, and in fact has been in Singapore and elsewhere around the world. More on that later. For this level of dynamic hypothesis formulation, consider the following dynamic formulation for the carrying capacity of water and society abstracted an infrastructure that increases the water resources in the city.

The cost of infrastructure depends very much on how much infrastructure there already is. It also depends on how much technology is required. The larger the production capacity of water infrastructure, the more technology is required to increase the infrastructure more. There are additional costs associated with the general maintenance and operation of the infrastructure. Operation and maintenance costs depend on the technology. At any given moment in time there is also only so much technology that can be mobilized to expand production capacity.

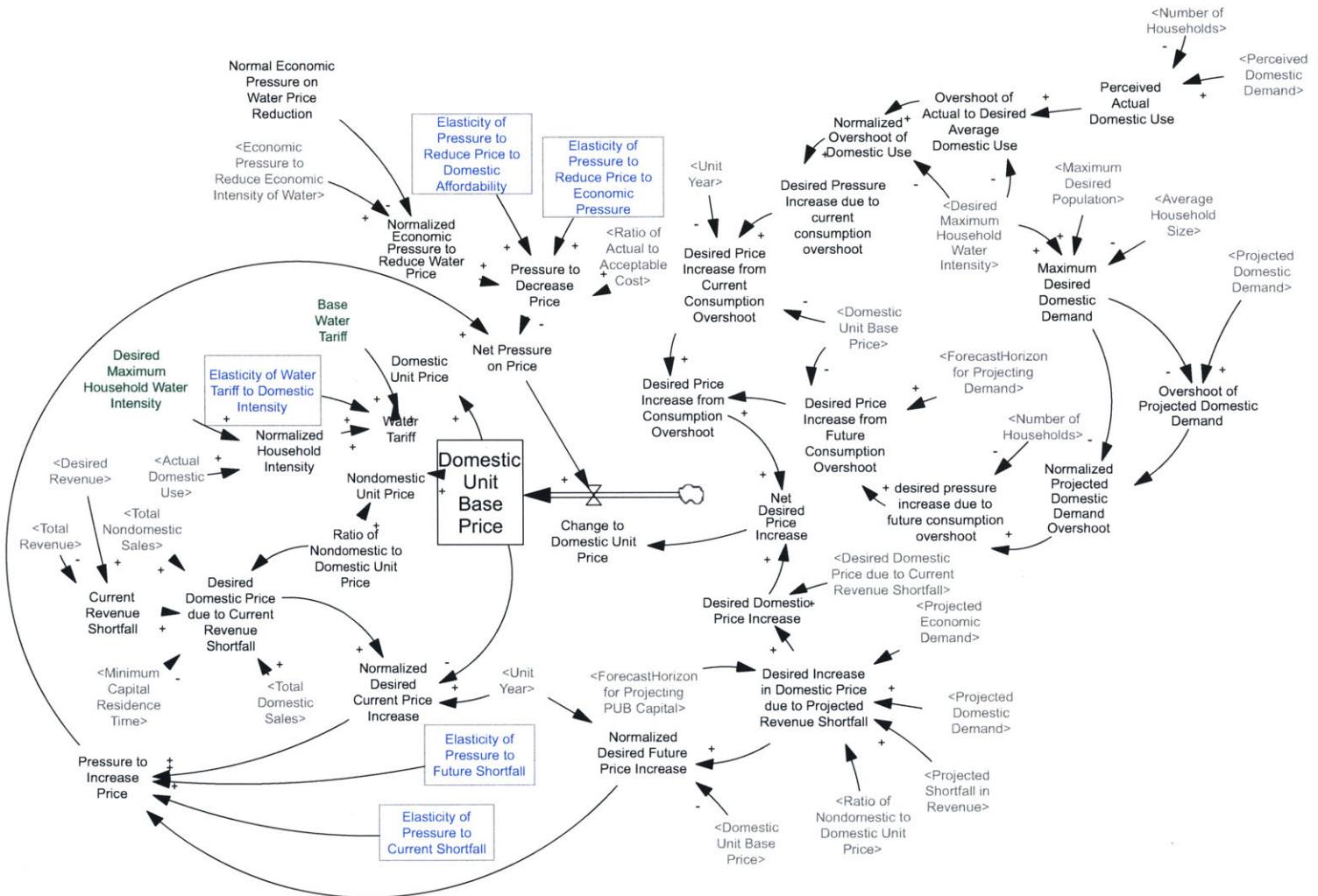
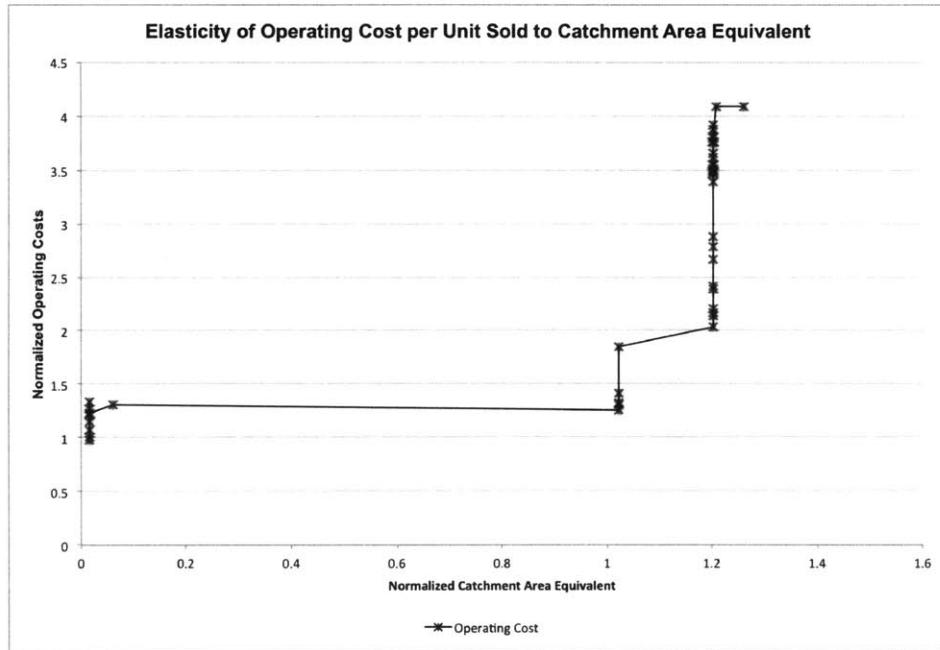
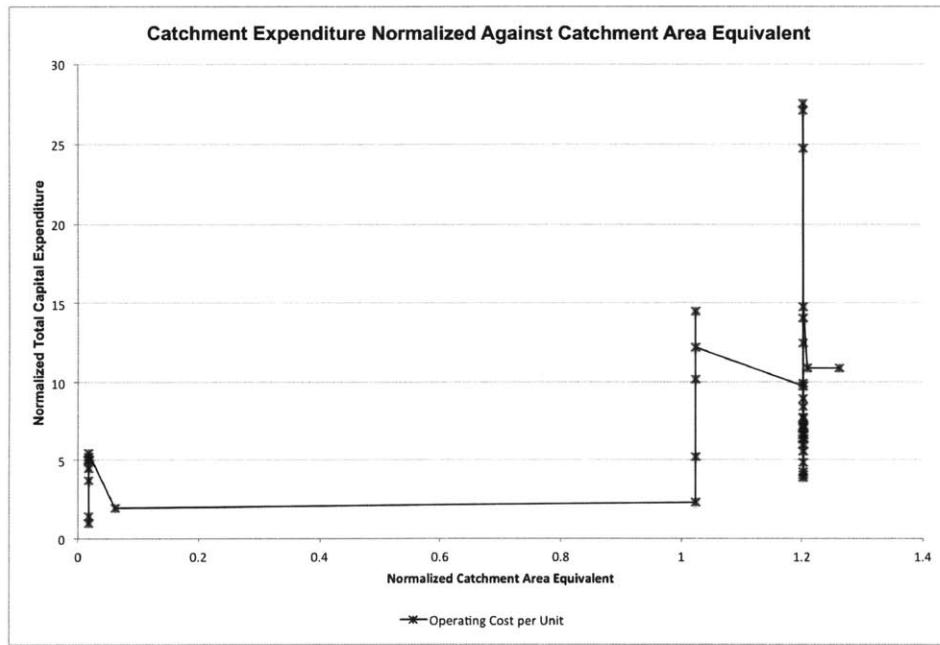


Figure 3-32: Figure showing the model structure for determining the water price



(a) Financial intensity of infrastructure operation



(b) Financial intensity of maintenance and infrastructure expansion

Figure 3-33: Financial intensity of infrastructure relative to installed catchment area equivalent. These graphs were used in the formulations for the table functions for the financial intensity of infrastructure, (*Graphed using data from PUB Annual Reports*)[2, 3, 4, 5, 6, 7, 8].

The relative financial intensity of infrastructure is an aggregate assessment of the character of the local resources. The lower quality or quantity the water resource is relative to demand, the larger investment in technology will need to be made. The relative financial intensity is therefore a metric associated with relative technological intensity and that is a measure of the quality of the local resource. Depending on the type of freshwater resource, some cities will start off requiring a more financially intensive water infrastructure than others. In addition this local resource has a carrying capacity that may be expanded with technology. Whether local climate, geology, proximity to a watershed, and proximity to the ocean, there are many parameters associated with each locality that characterize the set of water resources and the relative ease of accessing them. As these local resources are exhausted, it becomes increasingly more expensive to keep expanding access to water.

Operational costs per unit of water produced were graphed against catchment area equivalent normalized by total island area, as seen in Figure 3-33(a). The total island area is a measure of the local carrying capacity of the island for freshwater, since it is the main source for water flux. Although more data would better characterize the shape of the relationship between catchment area and financial cost for Singapore, the following graphs suggest an increasing financial intensity as installed catchment approaches total island area. These graphs were used as the table functions for determining the relative cost impact of infrastructure expansion through the course of the modeling.

In Figure 3-33(a), the operational costs per unit water produced were graphed against normalized catchment area as a measure of operational costs. The pattern suggests a series of levels with transitions at discrete points in the normalized catchment area. This graph could really benefit from having had more specific data about infrastructure costs and size. In Figure 3-33(b) the capital expenditures per unit water produced were graphed against normalized catchment area. This graph shows a more shallow and constant slope and less in the way of discrete intervals, but the data are still suggestive of levels. When the capital expenditures are examined over time as in Figure 3-29(b), there are a few points where the cost per unit water is much higher. Without specific data about infrastructure expansion,

this graph gives an idea of the frequency with which infrastructure is ordered and the relative size and cost of expansion. The baseline trend might be reasonably interpreted as maintenance cost per unit water produced. These baseline levels were used in calibrating the normal financial intensities of operation, maintenance, and infrastructure expansion.

Chapter 4

Results, Discussion, and Conclusion

4.1 Model Scenarios

The model scenarios were designed with attention to the variables and patterns of behavior that decision makers are expecting or are otherwise interested in. Stocks were initialized to 2010 values and are detailed in the equations for those stocks in the equation listing (see A.3.2). Growth in economic capital and population, factors pertaining to economic productivity, and trends in reduction of average economic water intensity were set to average historic values or the value required to replicate historic behavior.

Discussion with stakeholders and decision makers could give rise to a set of scenarios investigating how different trends would alter scenario results. For Singapore, population was assumed to grow at an average growth rate up to the maximum population level desired by policy makers. Since a couple of different levels have been identified, a lower bound of 7 million people and a higher bound of 8.5 million people were considered. Also, as of 2010, the baseline average household water intensity was set to $20\text{m}^3/\text{month} = 240\text{m}^3/\text{year}$, and if a household consumes above this level then the price per unit water increases accordingly as depicted in Figure 3-30(b). If there are an average of 5 people per household, this translates into a $150\text{L}/(\text{capita day})$, which is the modest level identified by policy makers as the average per capita consumption they would like to see achieved[35]. The desire to achieve this limit was input into the model as a policy feedback loop which monitored household consumption

and raised the price of water to leverage reductions in average household consumption.

Two sets of scenarios were formulated for investigating the capacity of the model to assess the time to water scarcity given the current management mode and trends in socioeconomic water demand. The first set of trends examines the expiration of the treaty with Malaysia providing water to Singapore. This scenario examines the sudden reduction in production capacity due to a loss of access to catchment area in Malaysia. Since policy makers have expanded desalination and reclamation as a replacement for this source, and those two production technologies are more financially intensive than rainwater treatment, the loss is associated with a change in financial intensity. The second set of scenarios investigates the vulnerability of Singapore's capacity to supply water to climate change, which has been identified as a scenario of concern to decision-makers[20]. These scenarios are summarized in Table 4.1. These scenarios include a change in three parameters: population, price policy, and precipitation, and for each of these parameters two options are considered, giving rise to four simulation runs examining system response to Johore and an additional eight simulation runs investigating climate change.

Table 4.1: Table summarizing of policy approaches and parameter values used in scenarios

Scenario	Number of Simulation Runs	Model Variables Changed	Stresses Examined	Range of Stress
Expiration of treaty with Malaysia	4	Infrastructure Production Capacity	Maximum Population	6-8.5
Climate Change	8	Financial Intensity of Water Infrastructure Production Capacity Financial Intensity of Water Precipitation Noise Amplitude	Financial Intensity of Water Maximum Population Financial Intensity of Water Precipitation Noise Amplitude	10% ramp or step price increase 6-8.5 10% ramp or step price increase 10% to 25% amplitude

4.1.1 Changing Cost of Water Infrastructure

Decision makers are expecting that in the year 2060, they will no longer have access to Malaysian water. They are planning infrastructure accordingly. Currently, desalination capacity has a production capacity of 200million m³/year. This will likely not cause great changes in the price of infrastructure construction, since infrastructure construction in recent years should already reflect the costs of the newer, more expensive technologies. However,

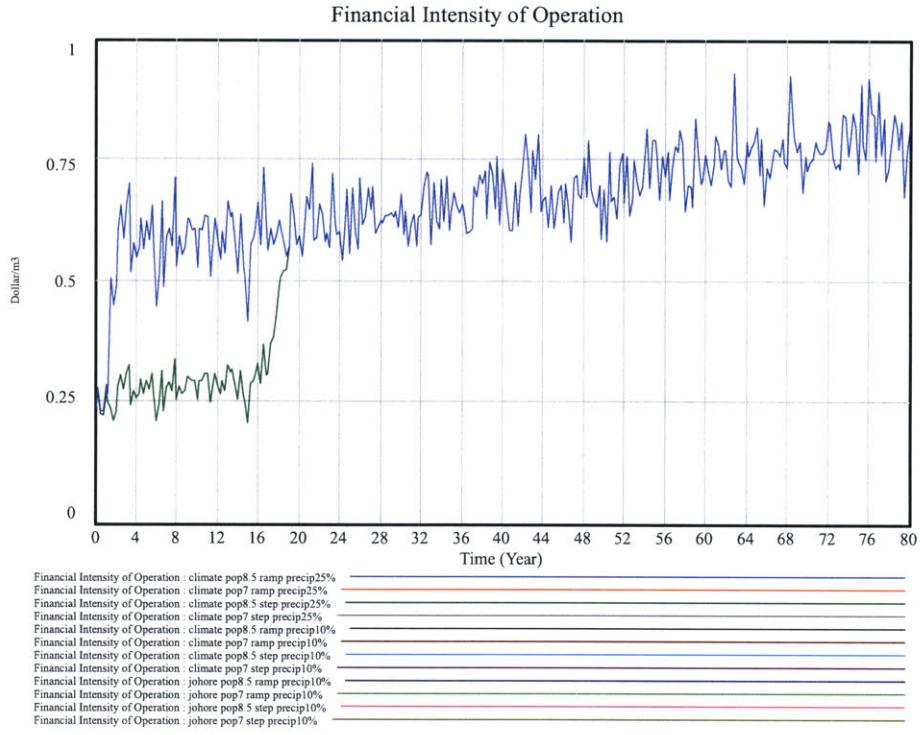


Figure 4-1: Financial intensity of operation adjusted for loss of Malaysian water.

especially as these newer technologies begin to account for a higher production volume, the cost of operation and management is expected to increase. The reliance on newer technologies would also increase the susceptibility of Singapore's water system to fluctuations in the energy market. This is true regardless of whether Singapore uses primarily reclaimed water or desalinated water, since both are energy intensive.

To investigate the sensitivity of the water system to these formulations, the loss of Malaysian water is represented in the model in a few different ways. First, infrastructure production capacity is reduced with a pulse with the magnitude of the production capacity of the installed catchment area production capacity of Johore. This formulation assumes that water infrastructure from Johore is cut off suddenly and permanently, resulting in a step decrease to infrastructure production capacity. Second, the normalized catchment area calculation is adjusted such that it does not drop relative to these numbers, as shown in 4-2(b).

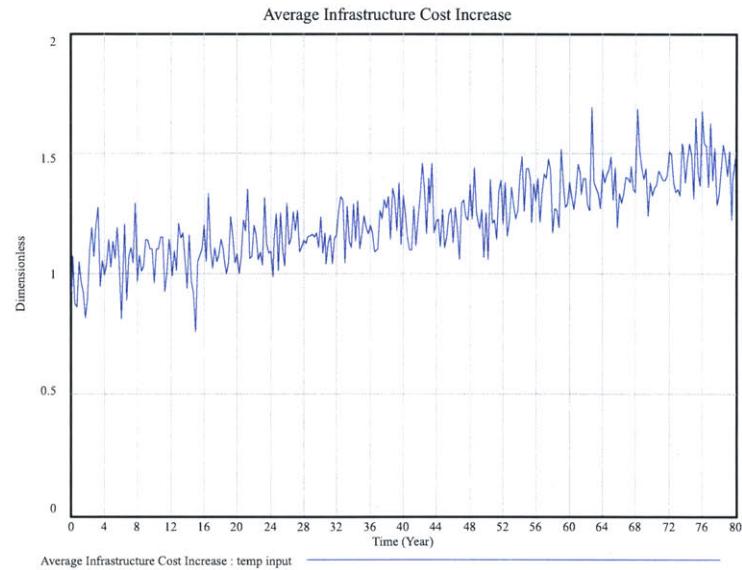
Since the formulation for normalized catchment area includes infrastructure production ca-

pacity and an adjustment for Johore already, this adjustment is taken out at the time of the treaty's expiration. This means that the financial intensity of infrastructure operation and maintenance, which are determined relative to normalized catchment area, do not decrease. This is because the type of infrastructure used in production does not change to the lower complexity-type infrastructure associated with lower values of normalized catchment area.

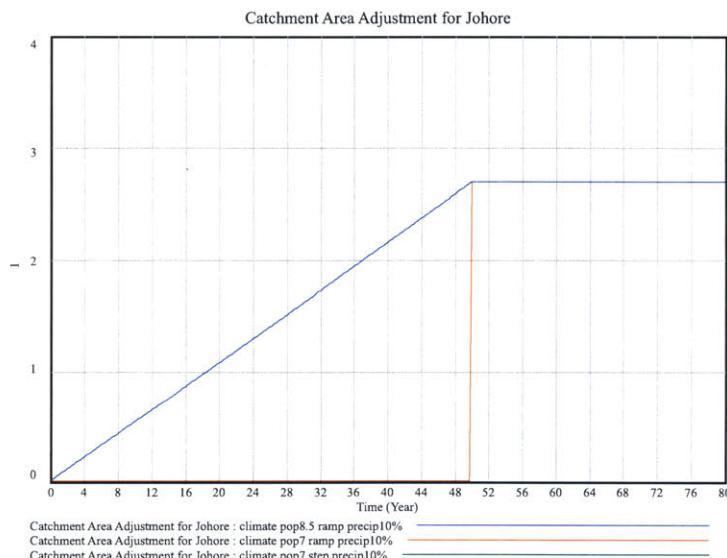
The financial intensity of operation and maintenance might undergo an increase associated with the adjustment in infrastructure. The reduction in capacity would be about 20% of current capacity, which is translated into an expected 10% increase in cost. This increase in cost was chosen rather arbitrarily and could be adjusted for expected real values. The scenarios explore two different policy approaches to price. The first policy approach is a step increase in price in the year in which water from Johore is cut off in order to offset the increase in cost associated with the more financially intensive infrastructure that will be used to produce water in lieu of water from Johore. The second policy approach is a gradual, linear increase up to level of the expected cost increase between 2010 and 2060. This second policy approach is modeled as a ramp function as shown in 4-1. Finally, these scenarios also include a changing cost of infrastructure over the next 100 years. The costs include a volatility in market prices by including a noise signal and a gradual exponential increase in price as depicted in 4-2(a).

4.1.2 Scenario: Climate Change

Climate change is associated with rising temperatures and changes in local weather patterns and overall climate[96]. Changing temperature is modeled as a linear increase in temperature between 2010 and 2110 of 3 degrees Celsius. This temperature range is within that suggested by the International Panel on Climate Change[97]. This temperature change included a gently oscillating signal to represent global fluctuations and potential volatility in average temperature, as shown in 4-4(a). Temperature is used as an input for determining the average losses to precipitation input from evapotranspiration, as shown in 4-4(c).



(a) Cost increase to infrastructure



(b) Adjustment to normalized catchment area for calculating financial intensity

Figure 4-2: Figures showing the changes made to model cost parameters for the scenarios examining the system vulnerability to the loss of the Malaysian water supply.

Climate change is also associated with changing precipitation and is likely to manifest as increasing variation from year to year. In order to investigate the affect this change in precipitation volatility to the stability of the water system, a low amplitude precipitation signal of 10% amplitude which roughly recreates historical variation is examined as a control, as seen in 4-4(b). The second climate change scenario considers a higher amplitude noise on the order of the largest difference between average and actual precipitation in historic data; the amplitude for this signal is 25% as seen in 4-4(d).

The amplitude of 25% was chosen by determining the largest historical swing between years of particularly high and low precipitation as observed in Figure 1-2(b). Potentially large changes in the temporal and spatial patterns of precipitation as a consequence of climate change are of particular concern to policy makers since they can give rise to devastating floods, droughts, and other problems[96, 98, 33]. Although numerical models cannot predict precisely how climate change will alter weather in specific regions, there is overall agreement that climate change will increase the variation in weather and the intensity of wet and dry periods starting within the few decades and likely lasting throughout the next couple hundred years[96]. In other words, more intense weather is expected to occur more frequently. For this reason, the 25% amplitude signal was chosen to represent a weather pattern on the order of the largest observed historical variation.

The main variables pertaining to these scenarios are depicted in the model view in Figure 4-3. This is the only model view that has not yet been shown and completes the pictorial documentation of model variables and feedbacks. Figure 4-3 primarily shows the model inputs. Management structures pertaining to these variables are depicted in previous model views.

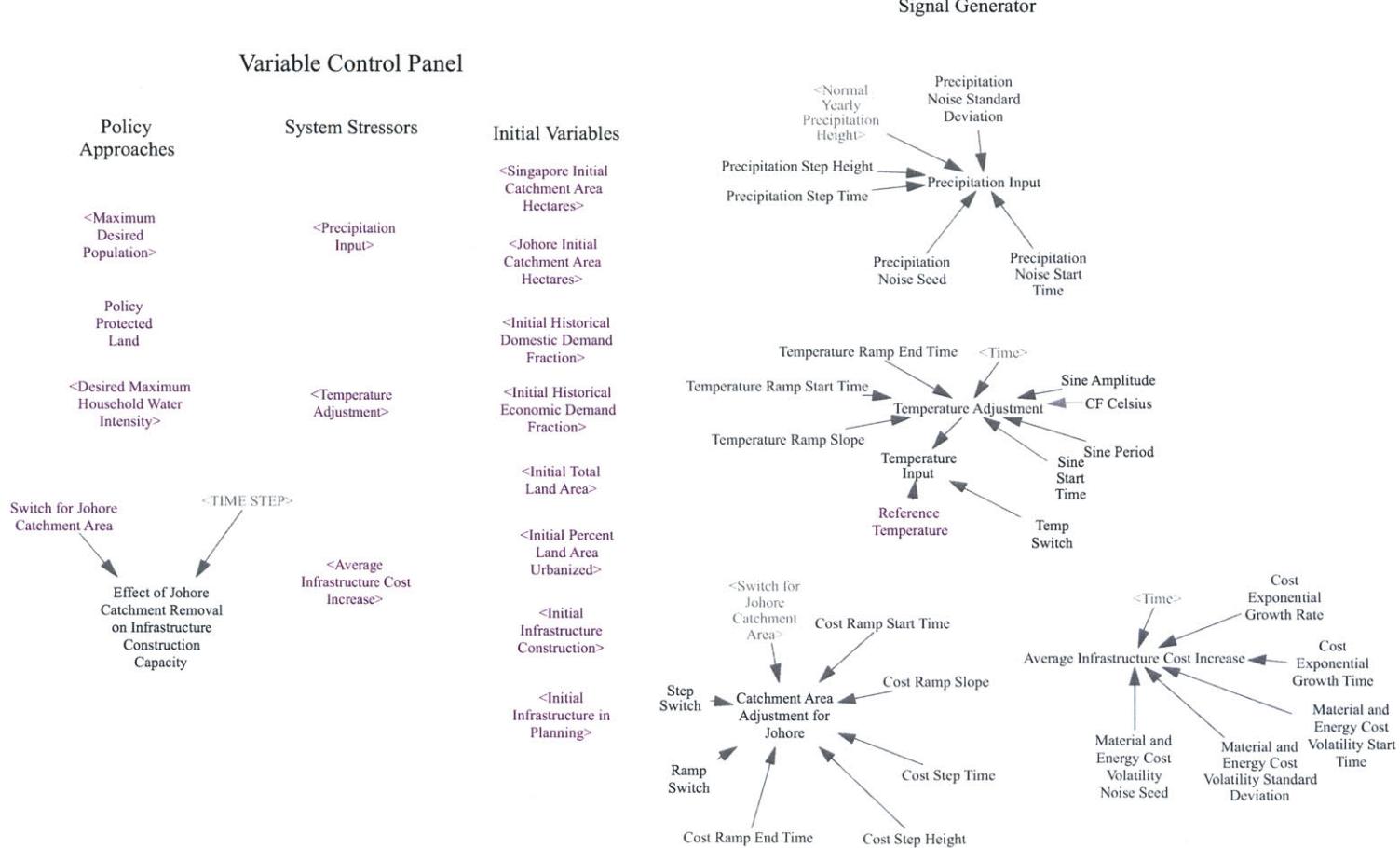


Figure 4-3: Figure showing the main policy and scenario parameters

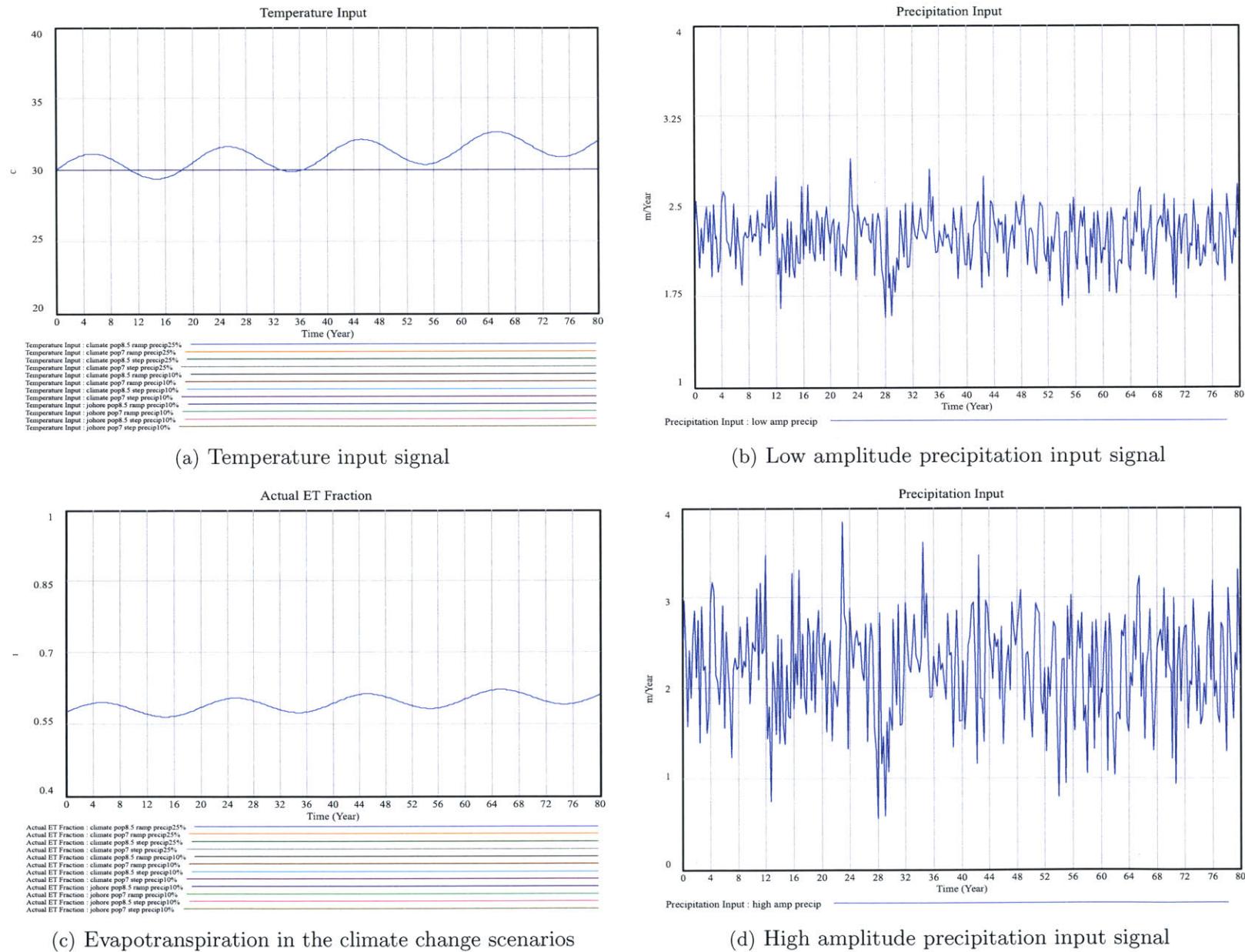


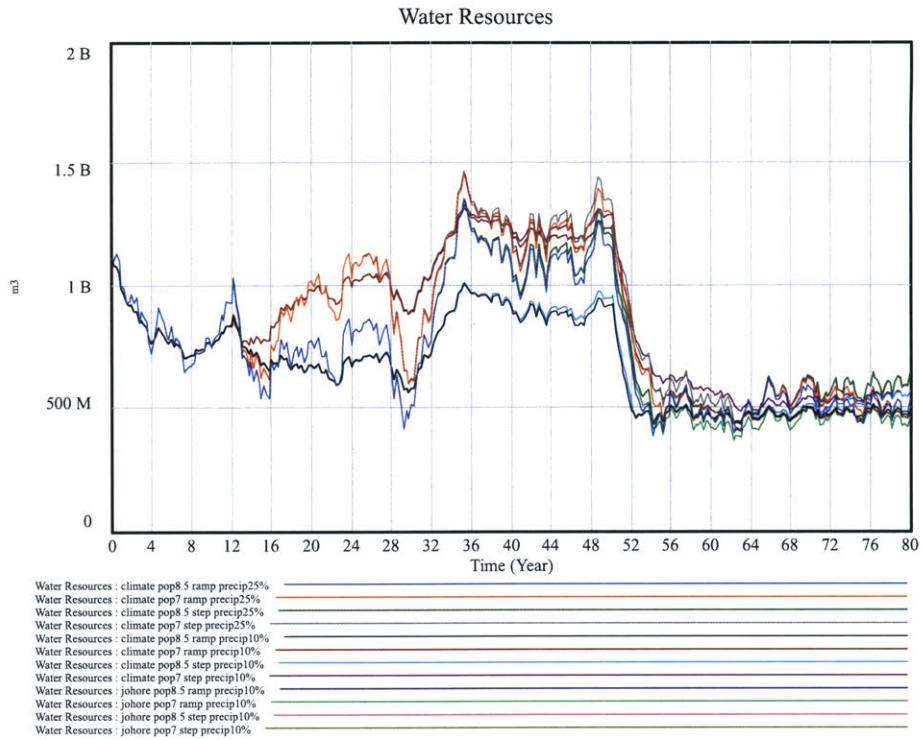
Figure 4-4: Figures showing the changes made to model climate parameters for the climate change scenarios

4.1.3 Scenario Results and Discussion

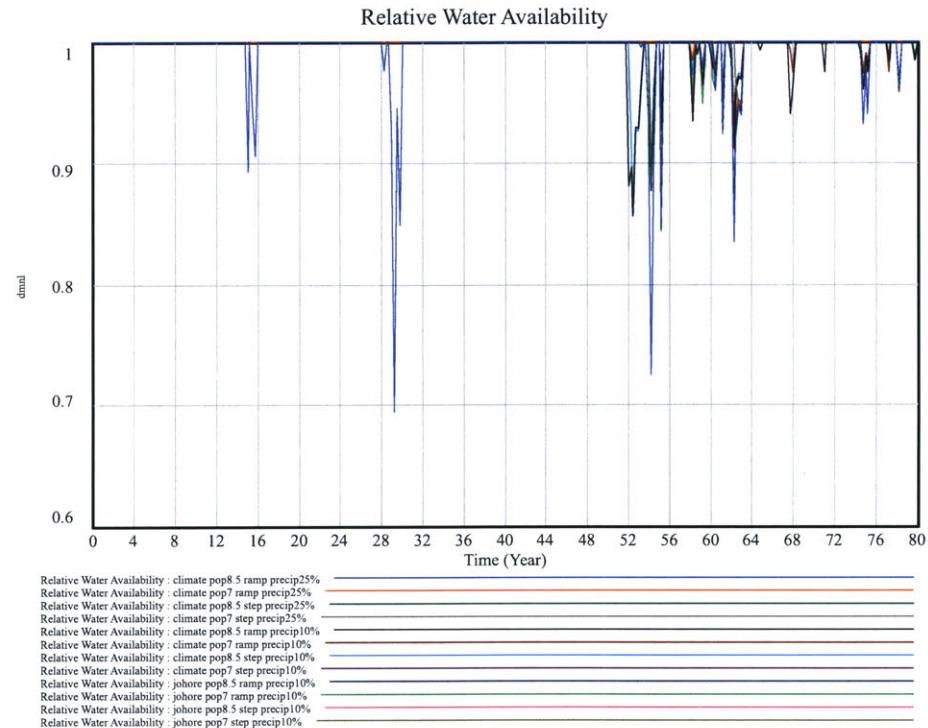
The model results indicate that Singapore's water supplies are susceptible to changes in precipitation, particularly when production capacity from Malaysia is lost. Policy makers may need to increase desalination and reclamation capacity even beyond what is required to replace the current supply of water from Johore in order to offset potential fluctuations in precipitation. Water produced from desalination should be less susceptible to fluctuations in precipitation and the formulation for desalination in the model should reflect this more than it currently does. Future tests should look into whether the vulnerability to climate change seen here accounts for the increase in production capacity due to desalination. However, desalination would be more susceptible to fluctuations in energy prices, and future iterations of the model would benefit from a more explicit feedback between water and energy.

According to the model, for all scenarios Singapore's water supply is sufficient to provide a sufficient supply of water throughout the next 100 years. There are times when the availability falls below zero, and this is not because the infrastructure production capacity fails to meet demand nor is it because PUB does not have enough capital, even with the increasing cost seen in 4-1. However, there are occasionally times when PUB requires an inflow of capital from the government for expanding infrastructure, as seen in 4-7(b). Singapore's government plans ahead for this type of situation, but for other cities whose central governments do not have a sufficient supply of such capital their water supply may be vulnerable to financial stresses.

The model runs show differences depending on whether the price was gradually raised up to offset the change from Malaysian water to more financially intensive types of water, but the overall difference was small. However, given the past sensitivity testings and the assumption of continued economic growth, it is important that policy makers carefully monitor water demand from nondomestic sectors since this could alter the overall trend in socioeconomic demand over time.

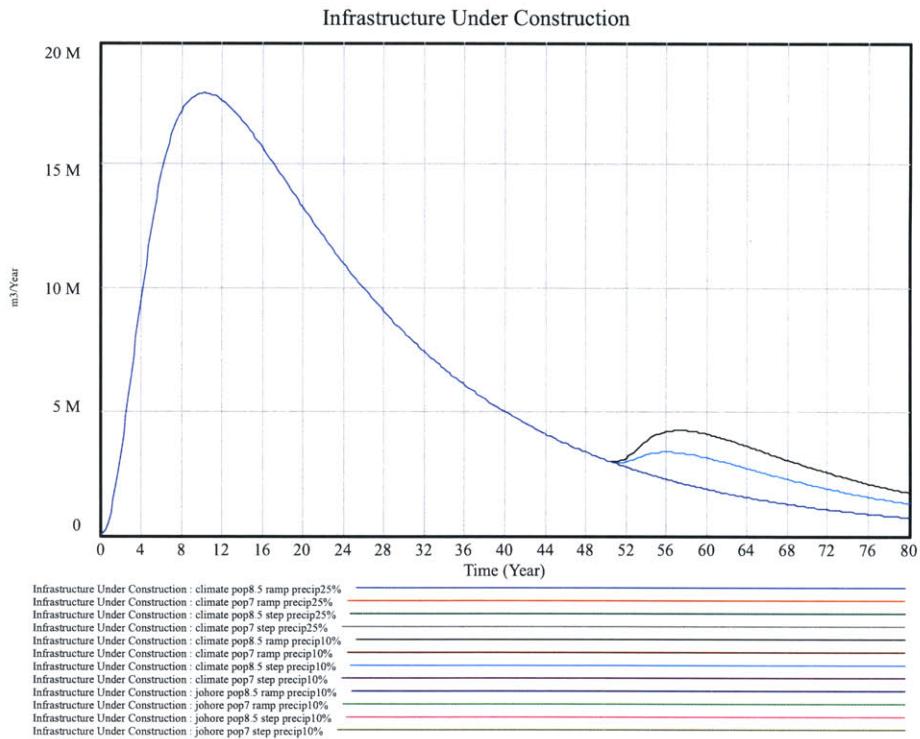


(a) Model results for water resource dynamics

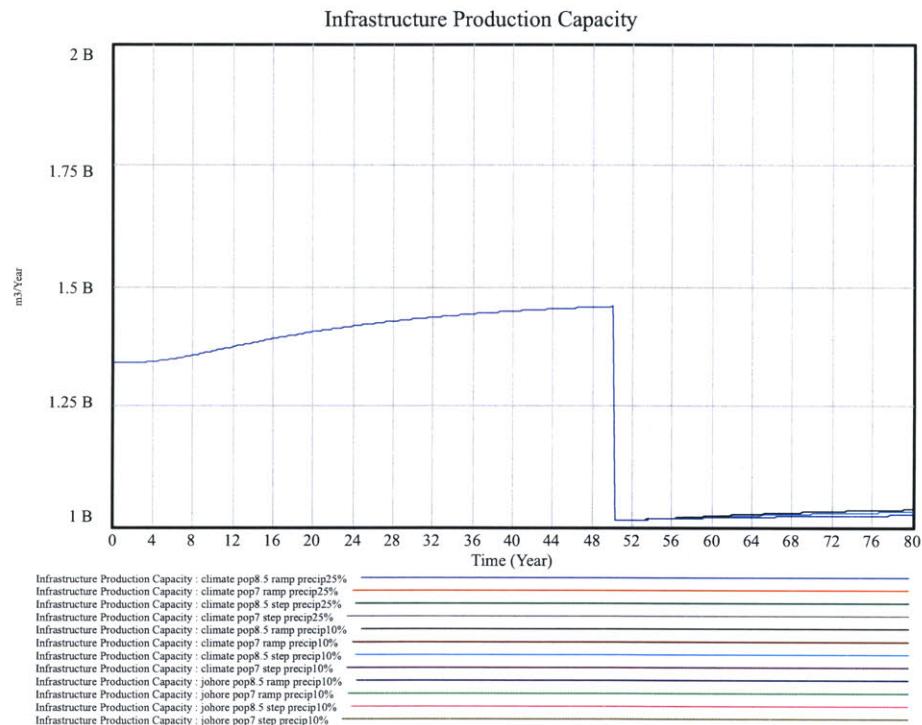


(b) Relative water availability

Figure 4-5: Figures showing the model results for water resources and relative water availability.

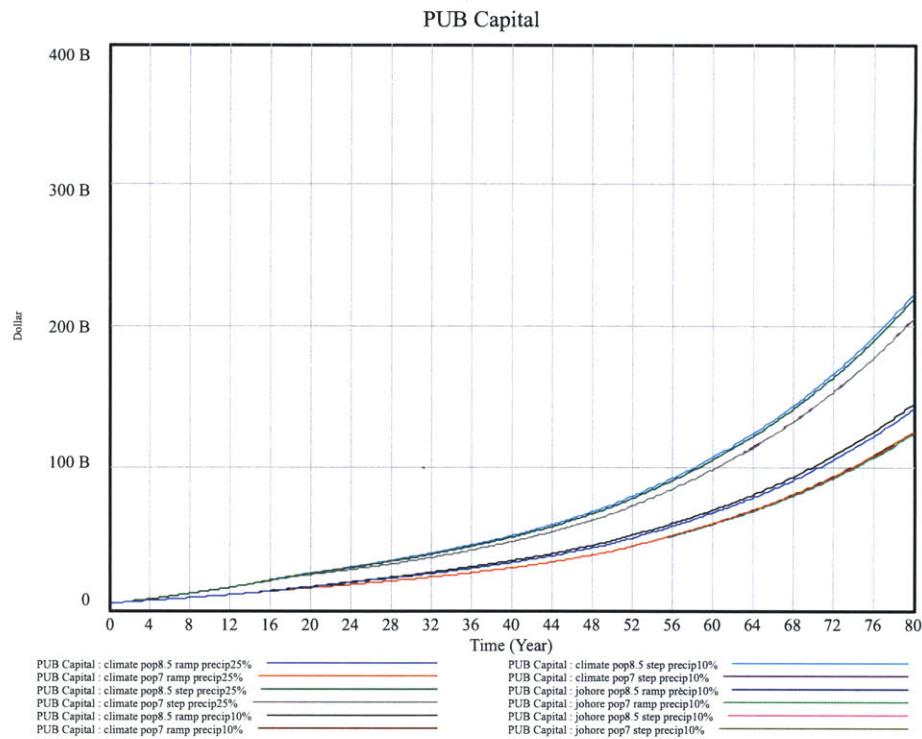


(a) Infrastructure under construction

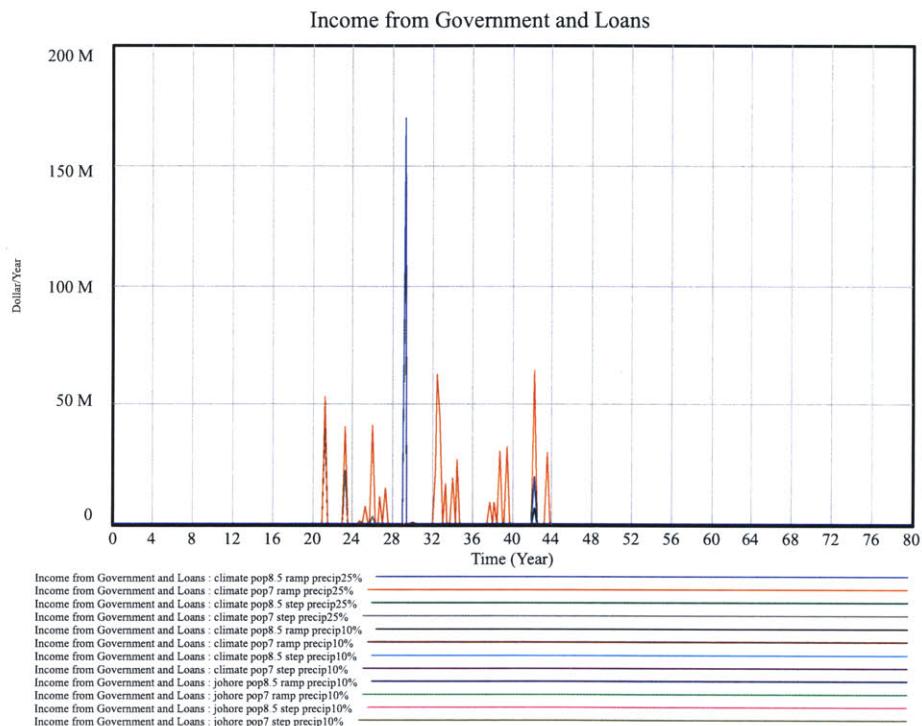


(b) Infrastructure production capacity

Figure 4-6: Figures showing the model results for infrastructure production capacity.

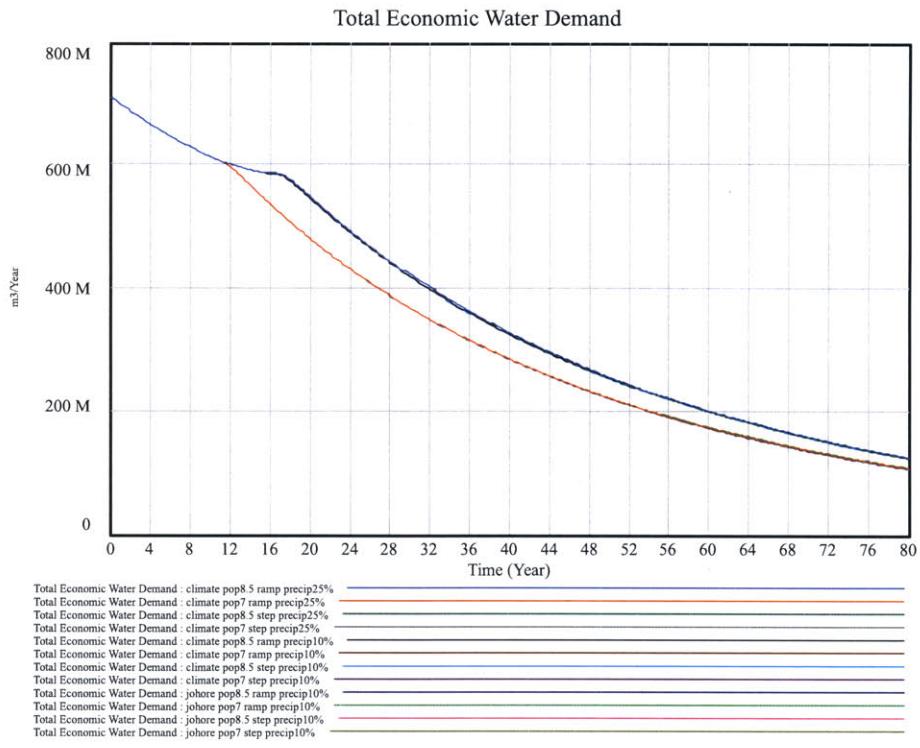


(a) PUB capital

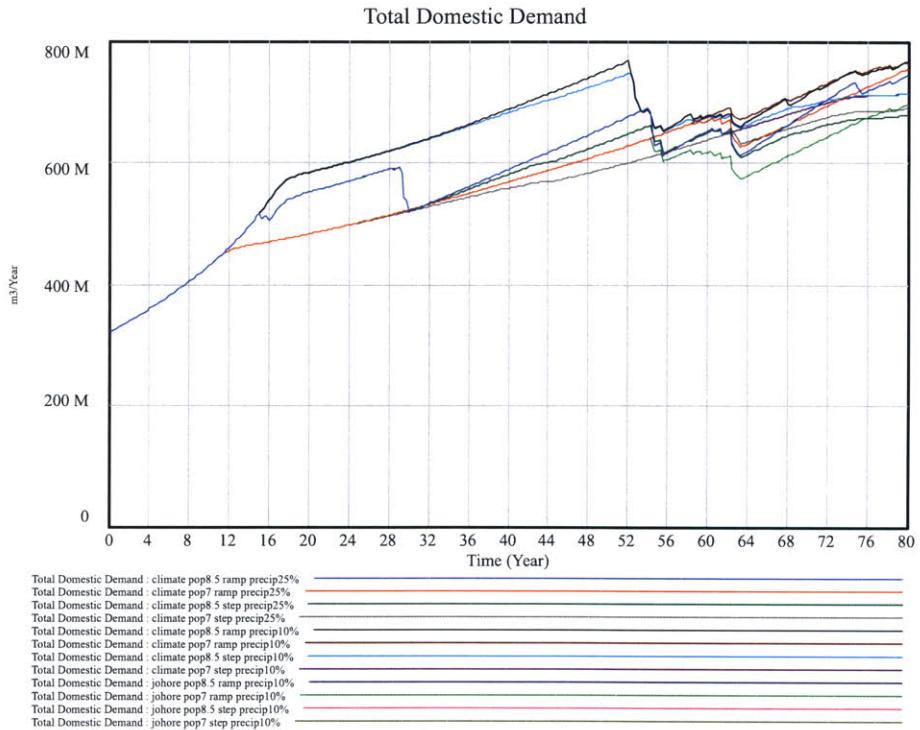


(b) Income from government and loans

Figure 4-7: Figures showing the model results for PUB financial resources.

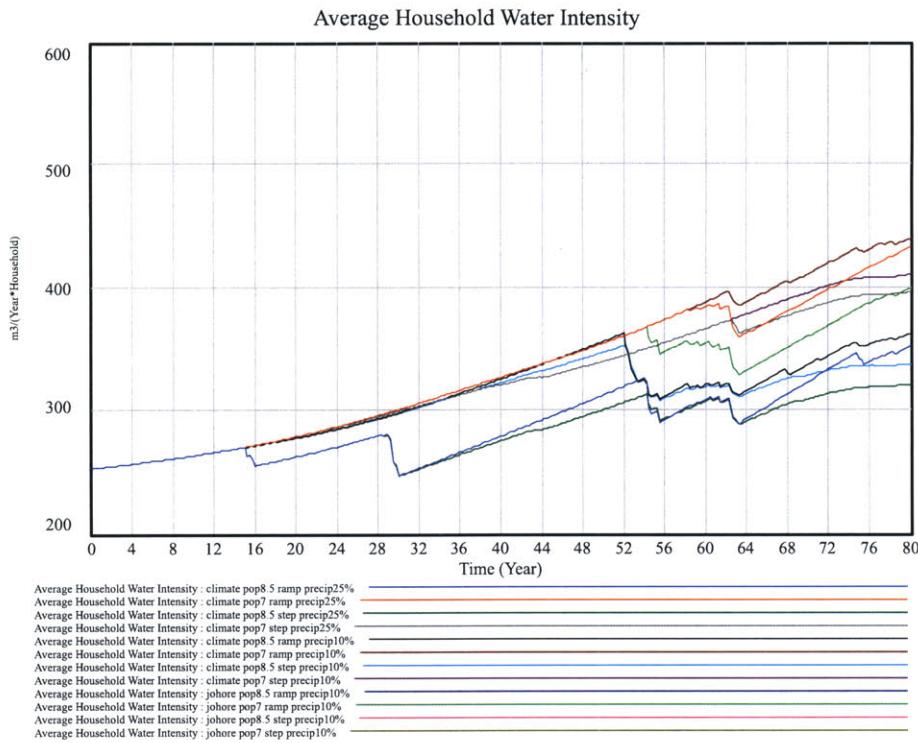


(a) Total economic demand

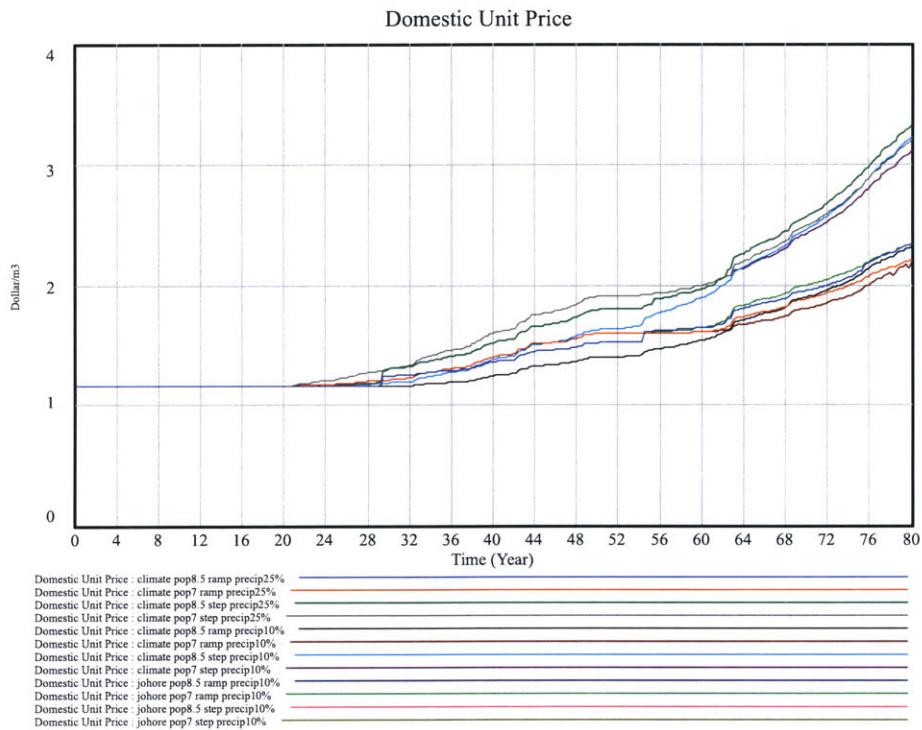


(b) Total domestic demand

Figure 4-8: Figures showing the model results for relative contributions to total socioeconomic water demand from nondomestic and domestic sectors over time.



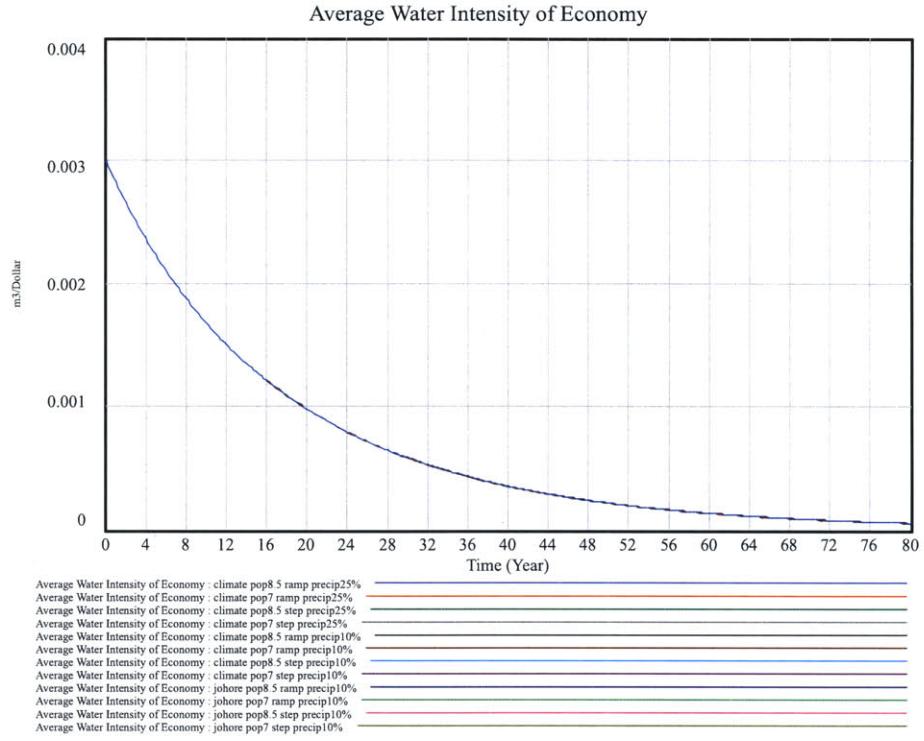
(a) Average household water intensity



(b) Domestic unit price

Figure 4-9: Figures showing the model results examining average domestic water intensity relative to domestic unit price.

Figure 4-10: Average economic water intensity.

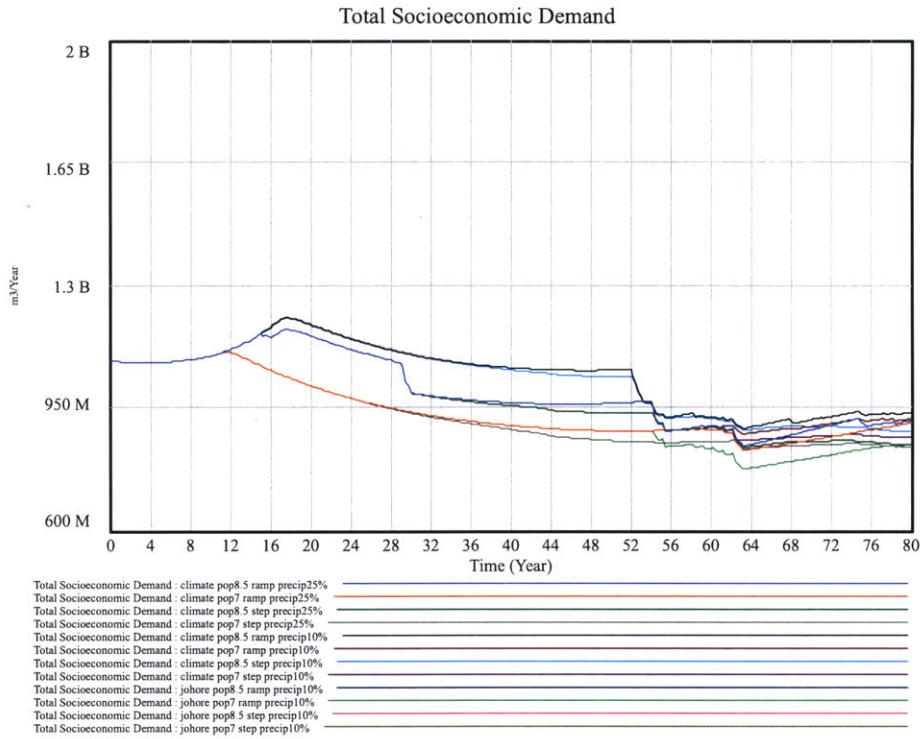


Average economic water intensity did not alter much between model scenarios, as depicted in 4-10, which is not surprising since it was formulated so as to not be particularly sensitive to changes in availability but instead to exogenous financial pressures.

Given the assumptions in the model about how average household water intensity responds to availability and affordability, it is most likely that average household water intensity continues to grow as long as household affluence continues to grow, as seen in 4-9(a), but the increasing price shown in 4-9(b) keeps the demand from growing faster than it would otherwise. However, in comparing the average household water intensity in 4-9(a) with the associated overall domestic demand depicted in 4-8(b), it is observed that the highest average household water intensities are not always the highest levels of domestic demand over time.

The total socioeconomic demand in the model runs decreases over time but generally levels off as seen in 4-11. This leveling off depends strongly on overall decreasing economic water demand in the economy. The trend in total economic water demand affects the overall trend

Figure 4-11: Model results for total socioeconomic demand.



in socioeconomic water demand strongly and ultimately determines whether or not socioeconomic demand increases over time, levels off, or decreases, as seen in 4-13.

Whether total economic demand levels off over time or not also impacts the overall vulnerability of the water system to water stresses. As seen in 4-14(a), the more slowly average economic water intensity falls over time, the more susceptible the water supplies are to variations in precipitation and energy price. With economic demand dropping more slowly than indicated in the model runs, the time to water scarcity given current trends in infrastructure production capacity is about 5 years. The more slowly the average economic water intensity falls, the more susceptible the system becomes over time and in particular, given the historic management behavior, it seems that the desired infrastructure order rate is insufficient to meet demand and Relative Water Availability shows a chronic shortfall in many scenarios after year 10 for scenarios with a higher total economic water demand. This is in spite of the fact that average household water intensity is relatively modest and on the order of the level desired by policy makers, as shown in 4-12.

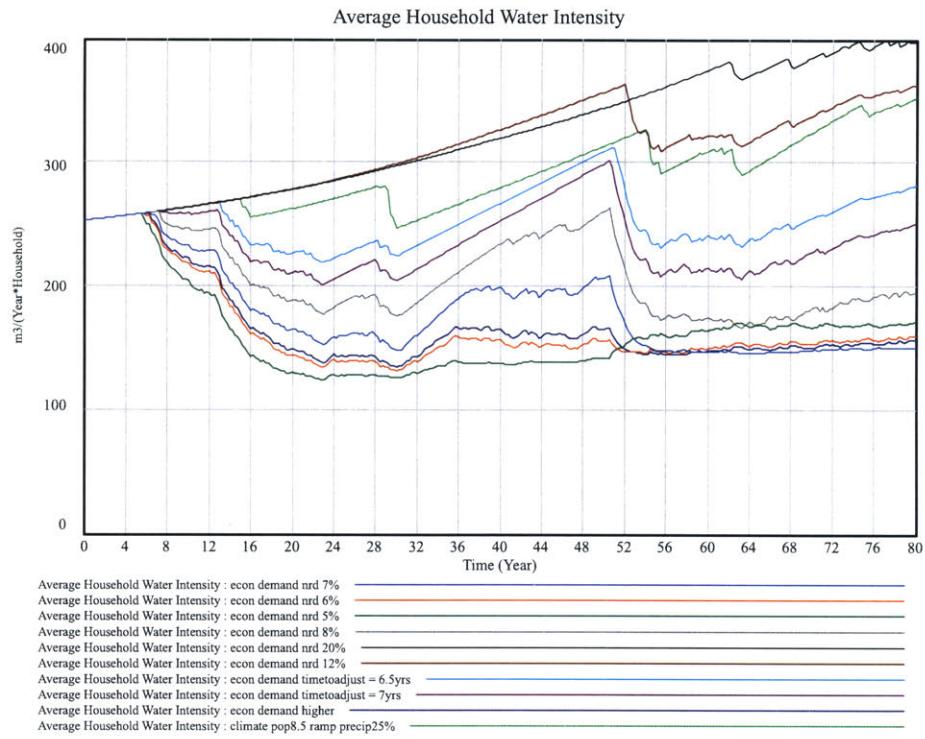
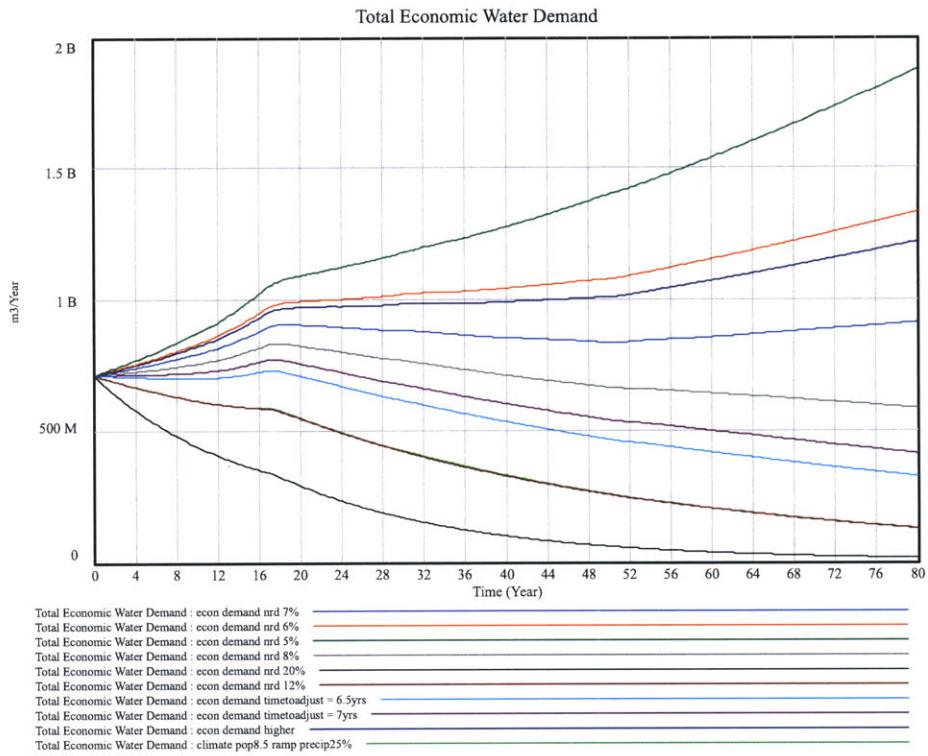
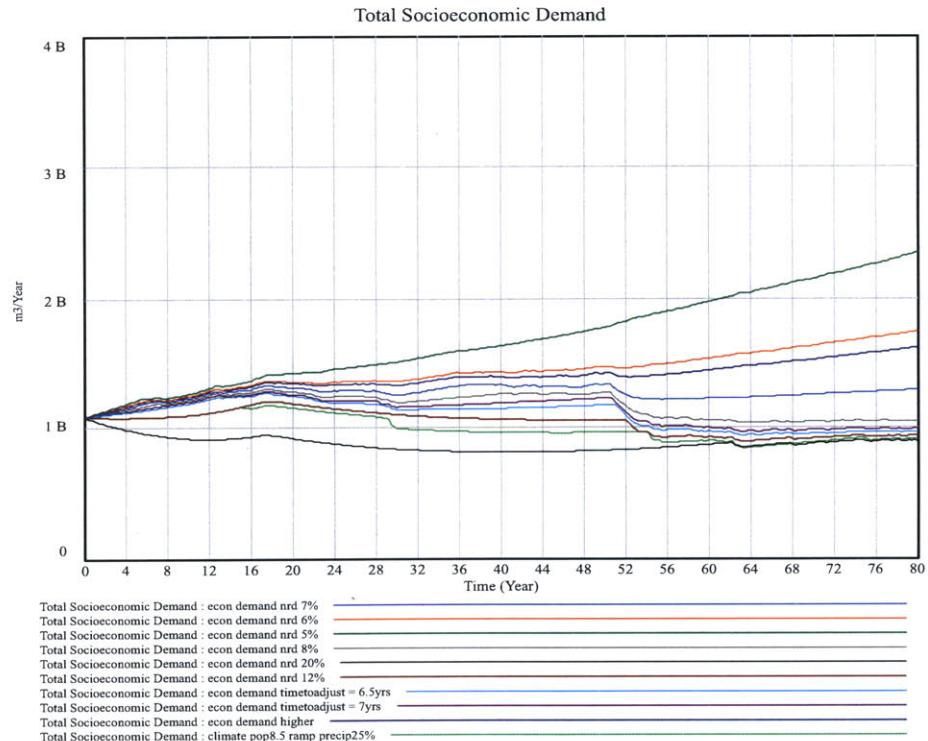


Figure 4-12: Average household water intensity for different runs of economic demand

This model result suggests that policy makers should consider policies that monitor nondomestic demand and average economic water intensity and encourage businesses and business practices that contribute to a faster reduction in economic water intensity. That average economic water intensity should be reduced more quickly is especially true if decision makers expect the rapid rate of economic growth to continue, since rapid economic growth when paired with higher relative average economic water intensities leads to higher socioeconomic demand over time.

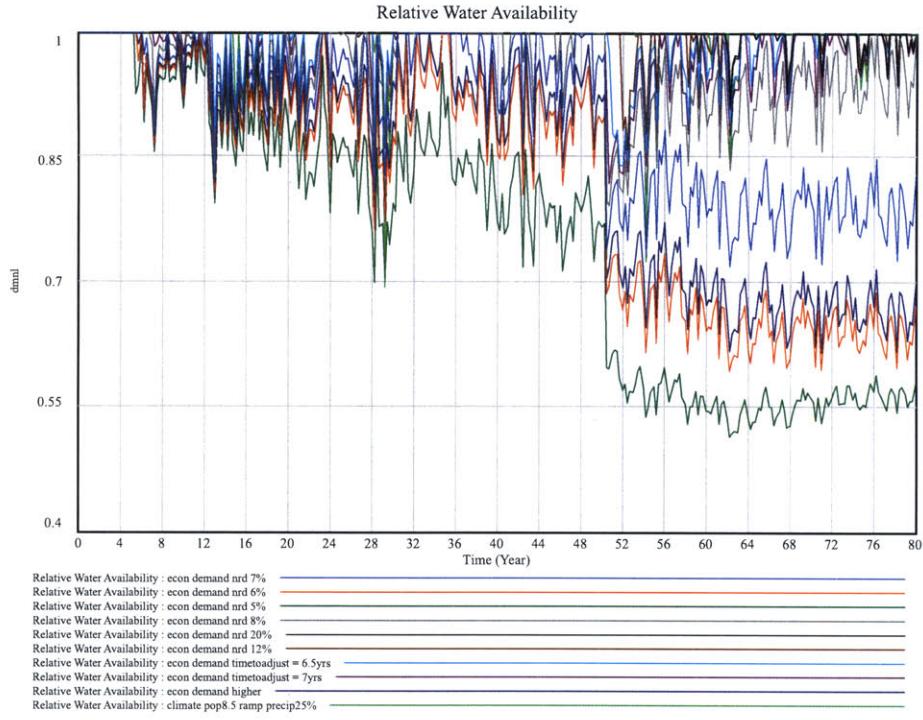


(a) Sensitivity of economic demand to net desired reduction



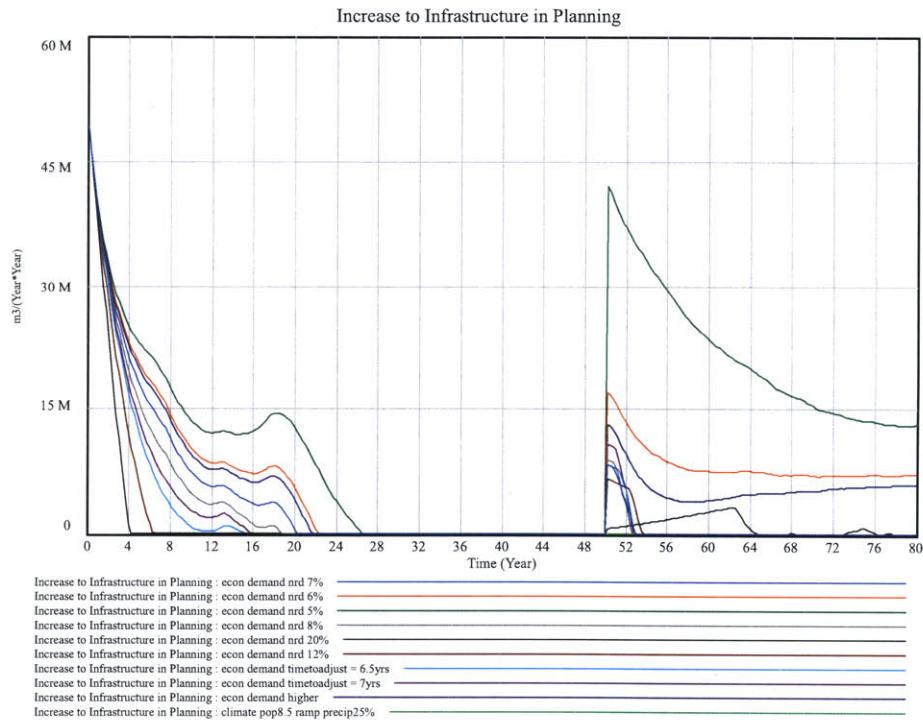
(b) Sensitivity of socioeconomic demand to economic demand

Figure 4-13: Figures showing the sensitivity of the total socioeconomic demand to the pace of reductions in average economic water intensity (scenarios changed Net Desired Reduction (NDR)).



- (a) Relative water availability falls short more often when total economic demand trends higher.

Figure 4-14: Figures showing the sensitivity of the model results to total economic water demand



- (a) Sensitivity of infrastructure order rate to net desired reduction

4.2 Conclusion

”All models are wrong. Some models are useful.” [21].

Recall that the *Limits to Growth* model was a System Dynamics model of global population and natural resources. It is useful to note, as Turner did, that “the World3 model was not intended to be predictive or for making detailed forecasts, but to provide a means for better understanding the behavior of the world economic system... Meadows et al. developed this understanding by experimenting with various settings of parameters reflecting different scenarios, and carrying out detailed sensitivity analysis, much of which is described in Meadows et al. (1974). The output graphs produced from the World3 model are predictive ‘only in the most limited sense of the word. These graphs are not exact predictions of the values of the variables at any particular year in the future. They are indications of the system’s behavioral tendencies only.’ (Meadows et al., 1972, pp. 92-93)” [15, p. 398].

The scenarios are dynamic simulations intended to indicate interesting scenarios and system behaviors. System Dynamics models are intended to replicate system behavior rather than predict[21]. For instance, the water system is vulnerable to changes in precipitation and particularly to large droughts. However, since the precipitation input is representative of what the precipitation input over the next 100 years might look like rather than will look like, the fact that water scarcity occurs in a year of drought must be understood to be relative to an exogenous parameter. In addition, although some management structures are modeled endogenously in the model, these formulations do not include the full formulation of how decisions are actually made, nor do they account for potential changes to that structure. Therefore, the scenarios and results must be understood to be informative about how the system might behave given existing trends and behaviors and not predictions of future events.

The System Dynamics model developed for examining Singapore’s water resource management in this thesis is unlikely to provide precise predictions of future water shortages. However, it should approximate the conditions under which the existing endogenously feedbacks

might give rise to water scarcity under changes in future external conditions.

The model results are considered to be the dynamic response of the system to relative changes in supply and demand. The graphs of Relative Water Availability in Figure 4-5(b) and in Figure 4-14(a) show the capacity of the system to supply water relative to demand. When relative water availability falls below one, the water supply infrastructure are no longer sufficient to meet demand. In order to examine which aspect of the system contributed most to the shortage, it is possible to work backwards from Relative Water Availability to the factors that contribute to it. If there is a shortage in production, does the shortage arise from a year of low precipitation or a year wherein PUB finances dropped so low that they could not afford to produce water?

It is also important to consider, with respect to the climate change scenario, that climate change may alter precipitation patterns in ways that do not have historical precedent in the particular region under consideration[17, 30, 96]¹ However, the magnitude of climate change that is expected given current conditions does have precedent in the geologic record[25]. Therefore, it might be of interest to policy makers to consider how vulnerable the water system might be to even larger changes to weather than have been observed historically. Considering that the model results to the 25% amplitude precipitation signal indicated that current water system management practices already leave the system vulnerable to large swings in precipitation, that result seems to suggest that even larger changes in weather would leave the system even more vulnerable.

Since the measure of the capacity of water infrastructure to generate supply, Infrastructure Production Capacity, is a aggregate metric, it cannot say what aspect of the infrastructure contributes to a limitation in supply. Moreover, it is important to remember that the Infrastructure Production Capacity is an aggregate metric for production that requires an

¹It is possible, though unlikely, that climate change may result in smaller variations in weather than are seen today. However, not only is this unlikely within the next few hundred years, it is also not considered in this particular scenario since the more stable the precipitation signal is, the more stable the water system will be relative to it[96].

assessment of the production capacity arising from interactions between the many types of infrastructure and processes that typically characterize urban water supply. The rate of deterioration and the cost of maintenance should be estimated by water system experts have have an idea of what is deteriorating within the system and how that is likely to affect the overall system capacity. Since there are many integrated water management models for many cities, these mental models can be verified if necessary in more traditional water models.

The delays that arise between the change, the identification of the change, and the implementation of infrastructure or management policies to adapt the system to the change all contribute to system vulnerability to climate. PUB's careful financial management, based on the assumptions in this model, seem to suggest that Singapore's water supply is at this stage more vulnerable to climate change than changes in infrastructure costs. However, if Singapore does move to supply 80% of demand from desalination and reclamation as they plan, the system is likely to become more unstable relative to changes in the costs and supplies of material and energy. The links between the water and material and energy sectors could be made more explicit than they have been made in this model. It would be interesting to create scenarios about how material and energy interact with the water system, what changes in the world market might look like, and how the system would respond to them.

Not all of the assumptions made in the model could be verified by data or confirmed by system experts, so the model results for Singapore should be considered relative to the model inputs and not necessarily representative of Singapore's future per se. Relative to the goals outlined for the model, the model results illustrate that many of the goals have been met. The model was developed to be as adaptable as possible to other cities, as generic as possible while still capturing the important dynamics. Does the model capture the important dynamics? is a question that should be assessed by stakeholders in future model iterations. To really meaningfully assess how well they have been met would benefit from discussion with water system experts and policy and decision makers in Singapore. The next steps of the model would be to show the results in a workshop and get feedback on the results that were of interest to them and the concerns and criticism they have relative the credibility

of the model's approximation and the legitimacy of the results. To facilitate this type of evaluation, a more user-friendly interface could be developed and a questionnaire design to elicit open-ended criticism could be available. The results of this feedback would be applied to create a more formal data-collection methodology and also used to reformulate some of the model assumptions.

Is the model adaptable to other cities? is the second question that needs to be considered. If the model captures the important dynamics for Singapore, will it capture the important dynamics for another city that is not Singapore but similar to it? Will it capture important dynamics for a city that is dissimilar to it? The model formulations suggest that it can. The model metrics are aggregate enough that even though water systems are highly specific to the urban area they supply, it is possible to interpret them for a new city with different physical and social conditions. However, if the interpretation of model inputs for other situations is complex, it may not be adaptable in a useful way. This is one modeling goals that cannot be meaningfully assessed given the tests of the model that have been run. To do so, moving forward, would require using the model to examine the dynamics of other cities, documenting the challenge in adapting the data to fit the model, and an assessment by stakeholders in that city of the utility of the model results.

Aggregating many physically distinct volumes of water and distinct physical processes into a single stock may not replicate the System Dynamics of Singapore's water system closely enough. However, the goal of the model is to facilitate assessment of overall water availability relative to supply and demand. The aggregation of many demand processes and financial processes is likely to be on a similar order of aggregation and has precedent in other water models, and it is hoped that the results of the model indicate that the aggregation is still a useful simplification for purposes of identifying system vulnerabilities. Also, the intention is that the results contribute to discussion and critique with experts and also with water system planners about improving this methodology in the future.

Such an assessment by water and urban system experts would also benefit future iterations

and applications. However, the model is also intended to be integrated into models that investigate feedbacks between water system policy and policy in the materials and energy sector. It is important to begin discussions about such integration early in the modeling process to keep the scale of the model appropriate for a more interdisciplinary application. A model that specifically addresses particular concerns of one group of stakeholders may be less legitimate or salient to another group of stakeholders[42]. When the goal is an interdisciplinary model that is legitimate and salient to decisions relative to the urban system as a whole, and not just a particular policy sector, it is important to be clear about those intentions from the beginning so that the model does not evolve in ways that detract from the original goal.

Future iterations of the model should disaggregate economic productivity and economic capital into different economic sectors. Disaggregating economic processes should include the inclusion of feedback loops between water and the material and energy sectors. This would be an important direction for the model since the water and energy sectors each contribute significantly to demand in the other. This integrated approach would be particularly interesting for Singapore and other water-scarce regions that have installed or are investigating energy- and material- intensive technologies. Also, considering the sensitivity of long-term trend in water demand to trends in the economy, it would be interesting to consider more specific scenarios investigating potential economic development plans.

Future work might investigate the range of parameters pertaining to current urban water system dynamics and the resulting dynamic operating modes. Many of the exogenous input parameters pertaining to the water system in particular, especially time constants, buffers, and policies would be interesting points to examine. Another category of exogenous variable that is more complicated, but could provide interesting insight into system performance would be the elasticity functions. In particular it should be investigated whether these elasticities vary significantly between city to city or if they are relatively standard and applicable and that the main dynamic modes arise from other exogenous parameters.

Many biogeophysical and socioeconomic parameters and feedbacks contribute to the relative success or failure of sustainable resource management policies in urban areas. Considering the time and resources required to identify and implement policies, it is useful to compare a policy that was successful in one city with the situation, or to identify a particular policy was not a success in one city but might be in another. Water is one renewable resource for which demand is beginning to approach the magnitude of supply, a situation which motivates sustainable water management. In order to better characterize the state of future water supplies relative to demand, and the way in which water policies might contribute to preventing future water scarcities, this thesis has proposed a framework for examining the endogenous feedbacks in a particular urban area that impact water policy and future water availability. If this model is applied to many cities it might be possible to characterize the state of global water resource in a way that contributes to adaptation of water policy in one city for another. The way I think this could be done is by identifying the range of current and future dynamic modes and by mapping urban area based on the exogenous and endogenous parameters to which the model is particularly sensitive. This characterization might then be examined by other types of analyses such as that by Saldivar-Sali[81].

Overall, the model is capable of reproducing interesting system behavior that seems realistic. The model includes a dynamic hypothesis for socioeconomic demand and therefore provides an aggregated framework with which to examine trends in resource consumption, especially relative to water availability over time. Also, the model formulation includes a type of management and decision-making framework with which to consider goal-based resource policymaking for sustainability. In that sense, the model seems to meet the original goals. Whether the model can be useful in creating an urban typology and/or be used as a platform for considering integrated resource management for sustainability is yet an open question which could be the source of future investigations and model development.

The model has over 300 variables and 20 stocks and could achieve greater pithiness and aggregation. However, for a model of a complicated physical supply chain, the socioeconomic processes contributing to demand, and the mental model of its management, it still seems

a relatively simple model. It is my impression that the exogenous parameters used in the model can be calibrated without large data sets and still contribute to interesting, useful, and reasonable model results. This is an important result because there are many cities for which data is not available for one reason or another. In addition, the model as it currently stands produces results that reflect realistic system responses to system changes. This is an important step in modeling for policy- and decision-making because it provides concrete results that can be criticized and assessed based on the system understanding of experts.

The model reproduces the historical patterns on the same order of magnitude at least and for many of them with decent quantitative approximation. This is a significant result in that, given the number of variables and potential sources of error in the data and the potential for incorrect assumptions about feedbacks and their sensitivities, a propagation arising from uncertainty in any model parameter might be large. Based on the model's reasonable reproduction of historical behavior, it seems that the assumptions made in the model and the dynamic hypotheses are useful approximations of urban water system dynamics. On a more personal assessment of the model results, I find the model to be a useful platform for investigating the feedbacks between different types of water policies and will likely continue to iterate and improve the model for my own academic use.

Appendix A

Supplement to Background

A.1 Background on Modeling with System Dynamics

A.1.1 Basic System Dynamics

Table A.1: System Dynamics vocabulary

Word	Synonyms	Definition
Feedback loop		A process whereby a change in one variable, due to connections with other variables in the system, creates a force of change that acts upon the first variable.
Positive feedback loop	Reinforcing loop	Refers to a process where a change away from a particular state leads to a force that propels the system in the direction of the change and away from the original state.
Negative feedback loop	Balancing loop	refers to a process where a change in the state of the system gives rise to force in the system that propels the system back towards its original state[21].
S-shaped growth	Goal-seeking	Refers to growth or decay where the system first undergoes exponential change and then levels off as the resources required to feed the reinforcing loop exhaust themselves.

Some of the important System Dynamics vocabulary is presented in Table A.1. This section offers a brief survey of basic interrelationships in systems and the dynamic modes these interactions give rise to. Many complex behaviors can arise from interrelationships and delays between apparently simple dynamics of subsystems. For a more in depth coverage of this very interesting material, please refer to *Business Dynamics*[21] and *Modeling the Environment*.

ment[37].

Dynamic behavior can essentially be broken down into several main types of behaviors. More complicated system behaviors arise from interactions between the many smaller subsystems that make up a larger system.

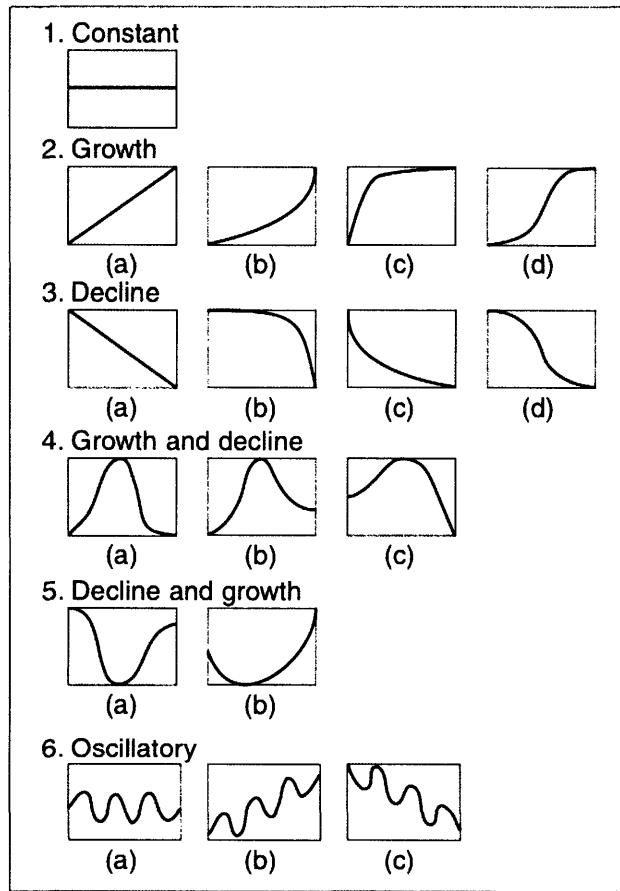


Figure A-1: Figure showing the main dynamic modes of system behavior.

Single-Loop Modes

Exponential growth and decay are both processes that require only a single feedback loop to operate, and are the two types of behavior possible from a positive or reinforcing loop acting alone. The term feedback loop refers to a process where a change away from a particular state leads to a force that propels the system in the direction of the change and away from

the original state. There are two basic types of feedback loops: a positive feedback loop or reinforcing loop refers to a process where a change away from a particular state leads to a force that propels the system in the direction of the change and away from the original state, and a negative feedback loop or balancing loop is a process whereby a change in one variable, due to connections with other variables in the system, creates a force of change that acts upon the first variable. Reinforcing loops give rise to exponential growth and decay, and the net rate of change of the system is proportional to the state of the system. In both cases, it is important to note that the system gives rise endogenously to the two behaviors.

The differences in the two types of modes above can be illustrated by considering population. As an illustration of a reinforcing loop, consider birth rate: birth rates are proportional to the number of people in the population at any time, so an increase to the population from births will give rise to a large population which will increase the birth rate and so on. A balancing loop can be illustrated by considering death rate, which is also proportional to the population: a decrease in population will result in a smaller population and a smaller death rate, and then a smaller decrease in population due to deaths.

Multi-loop Modes

Simple Multi-loop Modes When a reinforcing loop combines with a reinforcing loop, the behavior is still exponential, and for a balancing loop, the overall behavior is still balancing. Considering balancing and reinforcing loops interacting together lead to more dynamic behaviors. For instance, if birth rate is equal to death rate, the population will remain constant, as in Fig. 1 of Figure A-1. If birth rate is higher than death rate, the population will grow, exponentially, as in Fig. 2b of Figure A-1 whereas if death rate is higher than birth rate the behavior in Fig. 3c of Figure A-1 will be observed. If death rates are higher than birth rates, the population will decay exponentially basically, an exponential growth operating in the other direction. This is a reinforcing loop/positive feedback loop. Fig. 2d and 3d of Figure A-1 shows a typical S-shaped growth, where at first the growth is exponential and then levels off: in this case the birth rate would be higher than the death rate and then

the death rate would increase until the population leveled off. This behavior is also known as goal-seeking behavior. Goal-seeking behavior is observed in systems where at first the reinforcing behavior occurs unchecked, and then as the resources to sustain that change are exhausted, the system approaches an equilibrium state.

Adding time delays to negative feedback loops increases the tendency for the system to oscillate [21, p. 23].

Multi-Loop Processes with Delays When balancing loops interact with reinforcing loops, and the balancing loops operate more slowly than the reinforcing loops (i.e. there is a delay relative to the behavior of the reinforcing loop), then the system will show local and global maxima and minima. These delays can lead to oscillation (as in Fig.6 of Figure A-1), decline and growth (as in Fig.5 of Figure A-1), and overshoot and collapse (as in Fig.4 of Figure A-1)[21].

A.1.2 Formulating IPAT as a Carrying Capacity in System Dynamics

The importance of IPAT as an heuristic for examining environmental impact suggested that in developing the dynamic formulation of the system it would be useful to understand the similarities and differences in formulation of carrying capacity and environmental impact. To better understand how IPAT might be interpreted for a dynamic system, a thought experiment was performed to consider the relationship between environmental impact and carrying capacity.

Modeling the Environment in Dynamic Equilibrium

The thought experiment begins by considering an ecosystem isolated from and unaffected by society. Making the assumption that prior to the arrival of people the ecosystem is "healthy"

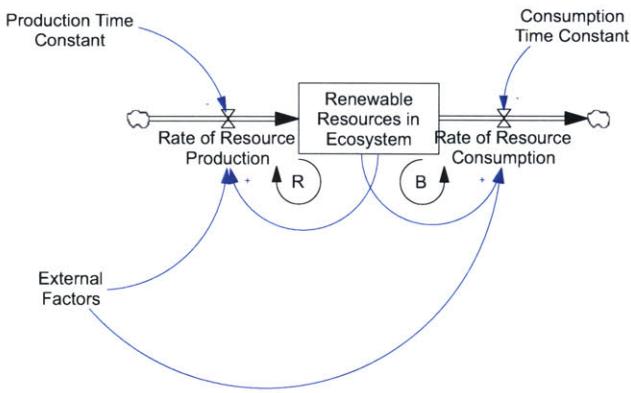


Figure A-2: Conceptual stock flow model of renewable resources, elaborating on the stock-flow model in Figure 2-9.

and in a "normal" operating state. This normal operating state is the characteristic dynamic equilibrium of said ecosystem sans people. What exactly the dynamic equilibrium looks like depends very much on the ecosystem. In this dynamic equilibrium, renewable resources are renewed at a rate characteristic of the ecosystem, as diagrammed by the stock and flow in Figure A-2. The stock should be initialized to an equilibrium value that represents the state of those resources in that environment.

Modeling the Resource Requirements of Population

What happens when people arrive at our ecosystem in dynamic equilibrium? Well, the arrival of people alters the functioning of the ecosystem. Let's start by assuming that the population that arrives are hunters and gatherers whose lifestyle can be supported by materials available within our ecosystem under consideration. This population of people has certain requirements for resource consumption to support their lifestyle. The number of people that can be supported will depend on the availability of these resources in the ecosystem before their arrival. Whether water or deer, when people arrive they begin consuming the resources they need. The stocks (populations or whatever) of these renewable resources will drop relative to the initial dynamic equilibrium of the ecosystem before the arrival of people. The population of people will grow, as populations do, exponentially. If the population is not simultaneously altering the capacity of the renewable resources to regenerate at their

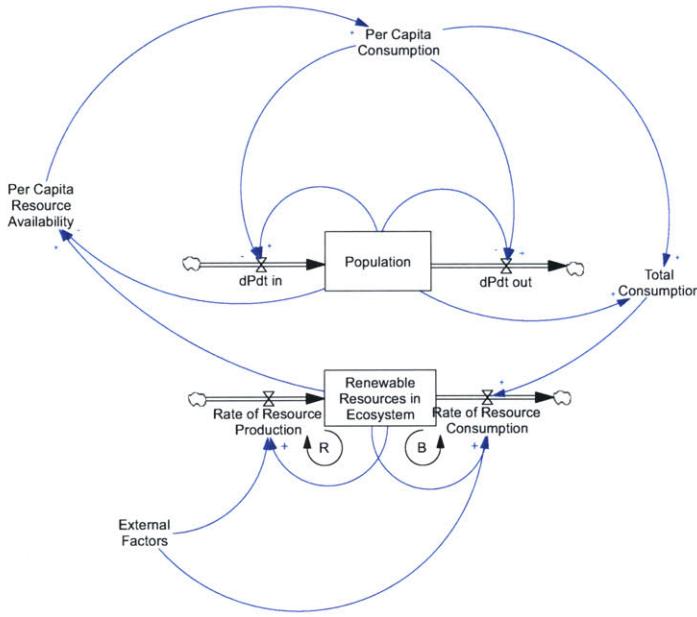


Figure A-3: Conceptual stock flow model of carrying capacity, elaborating on that discussed in Figure A-2.

previous rate, then it is likely that the population will follow an S-shaped growth trajectory (as discussed in Section A.1). The leveling off point of this population will depend on the resource requirements of individuals and the rate at which these resources are replenished. The population and stocks of renewable resources will come to a dynamic equilibrium at new levels.

Consider the mathematical formulation. At some time, t , an individual in this population has a demand for a renewable resource of particular type and quantity of resources, $e(t)$. If $P(t)$ is the population at that time, then the total demand for the resource is found by multiplying the per capita demand by the size of the population: $E(t) = e(t) * P(t)$. If the maximum quantity of resource which can be consumed without undermining the rate of renewable is E_{max} , then the carrying capacity of the ecosystem for that resource is given by $P_{max}(t) = E_{max}(t)/e(t)$. The carrying capacity of the ecosystem changes if either $e(t)$ or $P(t)$ changes.

Formulating Society's Modification to Environmental Carrying Capacity

People are quite adept at modifying their environment to expand its relative carrying capacity. In Figure A-3, the carrying capacity is determined by the per capita resource requirements of population. There are societal processes that both increase the per capita material requirements and decrease them, as depicted in Figure 2-9. In a sense, this modification of the environment to expand carrying capacity would be a an interesting interpretation of technology. Rather than going too deeply into philosophical considerations of carrying capacity and technology, let us consider some more straightforward interpretations. If a particular resource is required for survival, the carrying capacity may be expanded if a different type of previously untapped (or at least non-limiting) resource can substitute for the first. The new carrying capacity, might be given by $P_{max}(t) = (E1_{max}(t) + E2_{max}(t))/e(t)$, where $E1(t)$ and $E2(t)$ are the two resources. This formulation assumes that resource $E1(t)$ substitutes 1:1 for $E2(t)$, and that these resources are still the limiting factor determining maximum population. Ultimately, the resource that is scarcest even when substitutions are taken into account will limit the population.

The thought experiment above suggests the main requirements for interpreting IPAT as a dynamic stock-flow model. However, finding the carrying capacity is not as straightforward as the formulation suggests. First, the per capita demand for resources has a very broad range and can substitute many resources on for another. Additionally, ecosystems involve many positive and especially negative feedback loops that require that the changing of one resource will usually lead to the alteration of another resource. For instance, in most cases the system will not be in any kind of equilibrium. Resources might be diminishing, resource consumption might be increasing, and other critical variables might be changing in time. In this case, calculating carrying capacity as above would provide a misleading and therefore useless answer. It would be more accurate to find a carrying capacity that included feedbacks between different resources.

A.2 Background Information on Singapore

A.2.1 Back of the Envelope Calculation of Singapore's Yearly Volumetric Water Flux from Precipitation

To get an idea of the water resources of Singapore, a back-of-the-envelope (BOE) calculation of water flux from precipitation into the system is carried out as follows. First, the area of the island is required; the area of Singapore is approximately $700\text{km}^2 = 7*10^8\text{m}^2$.

$$Area = 7 * 10^8\text{m}^2 \quad (\text{A.1})$$

Second, the precipitation flux over this surface is required. It is known that Singapore receives an average height of 2m of precipitation per year (in the form of rain). This is a height input, \dot{q} , with units m/year. If we make the approximation that this point load is evenly distributed around the island, then the flux of water over the surface of the island is given by:

$$\int \dot{q} * dA = \dot{Q} \quad (\text{A.2})$$

If this is integrated over a time of one year and the area of the island, where the height input is assumed to be constant over the area of the island, then $\dot{Q} = 1.4 * 10^9$ with units m^3 . The maximum water demand, historically, is less than 1.4 billion m^3/year . Therefore, the volumetric water flux into the island is on the *same order of magnitude* as socioeconomic demand. Okay, but the estimate for volumetric flux is probably high; it is unlikely that, even though the humidity in Singapore is often near 100% humidity, all of the water that falls on the island is collectable. It is estimated that 50% of precipitation that falls in tropical climates is lost from evapotranspiration. This would still put water resources in Singapore at 700 million m^3 , which in 2005 would still meet over 50% of water demand. Well, it is said that the Marina Barrage increased the catchment area installed on Singapore from 50% to 66% in 2008, so it would be more accurate to consider the flux over half the island, which would again reduce the volumetric flux by half. This would provide about 25% of Singapore's 2005 water demand, which is much closer to (although still higher than) the 10% that Singapore's internal catchments are reported to have contributed to water supply in 2005.

It is interesting to note that there is still a potential untapped water resource for Singapore to access.

A.2.2 Additional Reference Modes of Singapore

Figure A-4 represents the fact that not all GDP enters households as income. There are only two data points for average household income in the years 1980 and 1990. This graph is derived from census data on average household income, the GDP, the population, and the number of households. This data was not used in the model. Instead, it was assumed that 100% of GDP enters households as income.

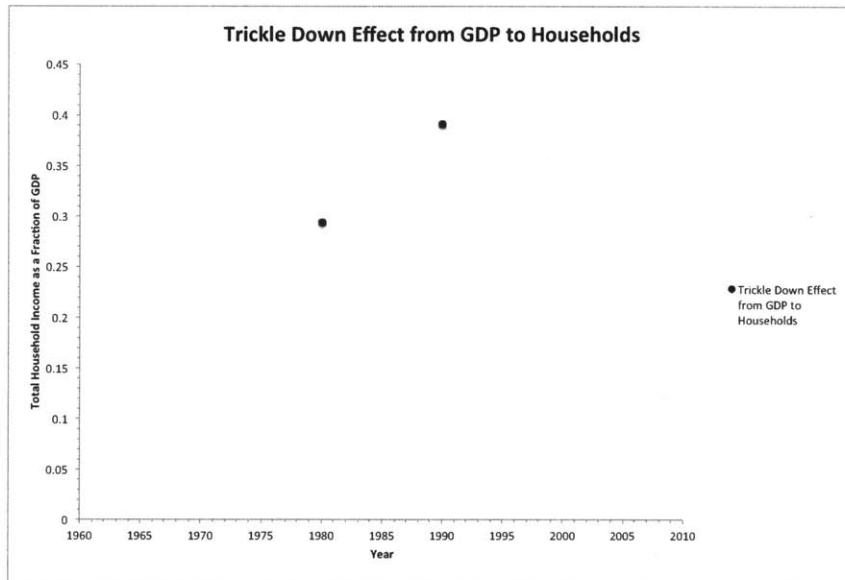


Figure A-4: Percent of GDP transferred to household income.

A.2.3 Timeline of Singapore's Water Management History

Chronology Timeline			
	Comments	Year	Event
World War II	Mr Tan Kim Seng made a donation of \$13,000 to enable supply of water to be brought into town from MacRitchie cost ~ \$13,000 Took 4 Years: started in 74 and finished in 78 Took 4 Years: started in 1890, finished in 1894 Sometime in 1890s: 1895 is placeholder Sometime between 1905 and 1920: 1910 is placeholder Sometime in 1920s: 1925 is placeholder Started off as zone rationing for six hours a day, four times a week, later extended to 12 hours a day, three times a week	1822	Small reservoir constructed at Fort Canning to supply water to ships
	1857	Singapore Waterworks started with a supply of water from MacRitchie Reservoir, flowing by gravity in a brick culvert to town Tan Kim Seng donates \$513,000 for construction of first waterworks and piped supply	
	1867	MacRitchie Reservoir completed	
	1868	Impounding reservoir constructed on Thomson Road using funds donated by Seng	
	1878	Expansion of reservoir; dam added to MacRitchie (completed 1878); pumping plant installed in MacKenzie Rd, Mt Emily service reservoir constructed	
	1890	MacRitchie Dam construction begins	
	1891	Thomson Rd Reservoir expanded	
	1894	MacRitchie Dam construction completed	
	1895	Slow sand filters at Bukit Timah constructed	
	1900	Distribution system extended along with expansion of storage and supply in order to bring freshwater supply to a greater number Increase in population causes new sources of water supply to be investigated	
	1903	Construction to raise MacRitchie Dam by 1.5m begun	
	1903	Pearl's Hill Service Reservoir construction began	
	1905	Construction to raise MacRitchie Dam by 1.5m completed (1982 capacity) Pearl's Hill Service Reservoir construction completed	
	1910	Kallang River Reservoir constructed; renamed Peirce Reservoir in 1922 more water mains laid; Woodleigh slow sand filters completed	
	1912	Kallang River Waterworks (Lower Peirce Reservoir) completed Woodleigh Treatment works completed	
	1920	permission granted to investigate water sources in Johore Seletar Reservoir constructed and expanded in 1940	
	1922	Thomson Rd Reservoir renamed MacRitchie Reservoir	
	1924	Construction on Gunong Pulai and Pontian Reservoirs (across the Causeway) developed	
	1925	new sources of water across the Causeway developed Fort Canning Service reservoir completed	
	1928	First pipelining across Causeway completed (water from Gunong Pulai and Pontian Reservoirs brought to Singapore) In addition to pipeline, pumping station and treatment works at Gunong Pulai and gravity main completed	
	1940	Seletar Reservoir expanded	
	1941	Gunong Pulai Pipeline duplicated from Gunong Pulai to Johore Bahru Treatment capacity doubled at Gunong Pulai	
	1944	Pulai I, a subsidiary reservoir feeding Pontian Reservoir, completed additions made to distribution mains and plants	
	1952	Tebrau Waterworks (across Causeway) commissioned	
	1953	Completion of Tebrau River works, including laying of steel pipeline through Johore Bahru Town and over the Johore Straits via the Singapore-Johore Causeway	
	1954	Scudia river scheme commissioned including river intake and pumping station, treatment plant, and pumping station	
	1956	Murman Service Reservoir completed (commissioned to improve water pressure and store adequate water for consumption)	
	1957	Jalan Eunos Service Reservoir completed (commissioned to improve water pressure and store adequate water for consumption)	
	1961	Treaty with Malaysia provides water from Johore to Singapore until 2011 for price of 1c/1000 gallons	
	1962	Treaty with Malaysia provides water from Johore to Singapore until 2061 for price of 1c/1000 gallons	
	1963	PUB came into operation as a Statutory Board to take over from the former City Council the responsibility of providing the people of Singapore with electricity, water, and gas supply Queenstown Booster Station completed (commissioned to improve water pressure and store adequate water for consumption) Queensway Booster Station completed One of worst droughts April, water rationing introduced, lifted after 10 months May, PUB established, charged with ensuring water assets would keep pace with population expansion	

Figure A-5: Timeline of important events in Singapore's water management history[20], *Continued on the next page*

Sometime in 1960s; 1965 is placeholder		1964	February, water rationing lifted as heavy rainfall returned
	Natural runoff from catchment is augmented by water pumped from seven adjacent streams and then pumped to Woodleigh Treatment works for treatment via Lower Peirce, requiring expansion of Woodleigh treatment capacity from 77000m3/day to 227000m3/day	1965	Singapore gains independence from Great Britain
		1965	Investigation of Johore-based Scudai River commences
		1966	Industrial Water Introduced with Jurong Island Water Works
		1967	Johore River Scheme completed; piped over Causeway
		1969	Reservoir at Seletar enlarged to 35 times its original capacity
			Pedok wells shutdown
		1969	Expansion of Upper Seletar Reservoir
			Expansion of eight stream abstraction stations
			Seletar Reservoir was enlarged by larger dam; Woodleigh water works expanded to increase treatment capacity, and one of two projects funded by World Bank Loan
	How far does the plan project forward?	1970	Pressure to reduce protected catchment area due to industrial and residential demand for land
			capacity of Jalan Eunos expanded
			First "Water is Precious" campaign
		1971	First Water Master Plan
			Bukit Timah Flood Alleviation Scheme Phase 1 completed
			Dry spell, no rationing required
			First Water Planning Unit set up to study scope and feasibility of new conventional sources such as unprotected catchments, and unconventional sources, such as water reuse and desalination
		1972	Jalan Eunos Booster Station and Water Tower completed in Dec 1972
			Singapore hosts workshop on water resources, environment, and national development in conjunction with the U.S. National Academy of Sciences
			Recommendations by Water Planning Unit as Water Master Plan; plan took 10 years to implement
		1973	Mount Faber II Service Reservoir commissioned
			capacity of Jalan Eunos expanded
		1974	First water reclamation plant constructed at Jurong (decommissioned in 1975)
	Construction of Western catchments water scheme involves construction of four reservoirs formed by damming the estuaries of the Sariibun, Murai, Poyan, and Tengah Rivers, as well as the extension of the Choa Chu Kang Treatment Works to a capacity of 364,000m3/day	1975	Upper Peirce Scheme completed; water treated at Chestnut Avenue Treatment Works
			Kranji/Pandan Scheme completed in 1975; water treated at new Choa Chu Kang Treatment Works
			Water reclamation plant decommissioned
			Estuarine reservoir: Kranji/Pandan scheme completed
			Upper Peirce Reservoir completed
			Chestnut Ave Waterworks completed
			Water Pollution Control and Drainage Act passed
			Peirce Reservoir split into Upper and Lower Peirce reservoirs to increase storage capacity
			Kranji and Pandan Reservoirs were first estuarine reservoirs, created by flushing out salty water over time
		1976	Water Treaty amended to continue providing water to new country of Singapore
		1976	Hill 65 Jurong service reservoir completed
			Choa Chu Kang Treatment Waterworks built to handle water from Kranji, Pandan, and Western Catchments
		1977	Western Catchments Water Scheme initiated
			Pulau Tekong Water Supply Scheme initiated
			Western Catchments Scheme commences
			Singapore River clean-up launched
			Trade Effluent Regulations introduced
		1978	
		1979	Pulau Tekong Water Supply Scheme completed
			Bedok WRP commissioned
		1980	Bukit Kallang I, Kent Ridge, and Nanyang I service reservoirs completed
			Kranji WRP commissioned
			Western Catchments Water Scheme completed
			Water Conservation Plan drawn up. Action includes educating public and giving advice on how to eliminate wastage and excessive use of water.
			Western Catchment scheme completes
			Seletar WRP commissioned
			Jurong WRP commissioned
			Western Catchment Scheme completed (Sariibun, Murai, Tengah, and Poyan Reservoirs)
			Expansion of Choa Chu Kang Waterworks
			First Water Conservation plan
			Singapore declared "malaria-free" by the WHO
			Pig farming and open duck rearing phased out of all water catchments
			Murai, Poyan, Sariibun, and Tengah dams were expanded, known as western catchment

Figure A-6: Timeline of important events in Singapore's water management history[20], *Continued on the next page*

		1982	By 1982, water supply consisted of 10 impounding reservoirs and eight treatment works [total treatment capacity of 130700 cubic meters/day] Kalang II completed
		1983	Water Catchment Policy introduced to control developments within unprotected catchments
		1984	Inter-agency Road Drainage Improvement Task Force established
		1986	Sungei Seletar/Bedok Scheme completed Bedok water works completed Sungei Seletar-Bedok water scheme developed; Sungei Seletar dammed to form Lower Seletar Reservoir; Bedok Reservoir constructed out of Sand quarry
		1987	Singapore River clean up successfully completed First Clean and Green week Bukit Timah Flood Alleviation Scheme Phase 2 completed Dry spell, no rationing required
		1990	Half of Singapore still untrapped as water catchment, including Marina Catchment, which represented 1/6th the land area of Singapore (10000 hectares); Marina catchment hadn't been accessed because oldest and most densely populated area and water quality had improved, but not good enough for treatment until technology made it affordable; planning for Marina Bay begins
		1991	Water Conservation Tax introduced
		1997	Water Pricing Restructuring Singapore served 100% by modern sanitation system Dry spell due to El Nino, no rationing required Lifting of 1983 Water Catchment Policy's urbanization cap and population density limit NEWater Study commences Commencement of DTSS Phase I Water Pollution Control and Drainage Act repealed and relevant powers streamlined into Sewerage and Drainage Act and Environmental Pollution Control Act
		2000	NEWater demonstration plant at Bedok commissioned
		2001	PUB reconstituted to become Singapore's National Water Agency and transferred from MII to ENV, becomes responsible for sewerage and drainage and allows for more holistic water policy planning Sewer Rehabilitation Phase 2 commenced
		2002	
		2003	NEWater Factories at Bedok and Kranji begin operations ENV renamed Ministry of the Environment and Water Resources (MEWR)
		2004	Third NEWater Factory at Seletar begins operations Reservoirs opened for recreational activities WaterHub formed Reservoir Integration Scheme commenced
		2005	Tuas Desalination Plant opens at cost of 200M USD; provides 114000m ³ /Day Environment and Water Industry Development Council formed under MEWR
		2006	Private Sewer Rehabilitation Programme commenced Sewer Rehabilitation Phase 3 commenced ABC Water programme launched
		2007	Clean and Green Week rebranded as Clean and Green Singapore PUB wins the Stockholm Industry Water Award Ulu Pandan NEWater Factory commissioned Reservoir Integration Scheme completed Energy Efficiency Master Plan introduced Reservoir Integration scheme completed; allowed water to be transferred between catchments for storage, effectively increasing catchment without expanding land
		2008	Inaugural Singapore International Water Week
		2008	Kim Chuan Water Reclamation Plant phased out
		2010	

Figure A-7: Timeline of important events in Singapore's water management history[20]

A.3 Model Documentation

A.3.1 Summary of Variables from Other Integrated Resource Management Models

A number of integrated water resource management models were consulted for identifying important processes and variables to model. In addition, these sources were consulted for precedent on how to model water resources through system dynamics. Some of the important variables and processes are summarized in Table A.4.

Functional Requirement	Design Parameter	Analysis	Metric	Unit	Unit	Physical Scales
Capacity to Produce	Natural Inflow Inflow from Society	Climate and weather Climate Patterns Topography Location inland or coastal Geology Land Use Technology to Produce Resources to Implement Technology	Precipitation Percolation Flow rate	Quantity of Rainfall Timing	Average Yearly Input Intensity Duration Frequency	
Capacity to Collect	Magnitude of Collection Distribution of Collection	Land Use Geology				
Capacity to Store	Storage Area Storage Containment Properties (permeable, semipermeable) Volumetric Storage Capacity Location relative to other system processes	Land Area Climate Patterns Topography Location inland or coastal Geology Land Use				
Capacity to Treat	Quantity of Water Required to Meet Environmental Goals Quality of Water Required to Meet Environmental Goals Quantity of Water Required for Socioeconomic Goals Quality of Water Required for Socioeconomic Goals	Pollution Technology Infrastructure Finances				
Capacity to Transport	Transportation Need	Transportation Rate Length and Distribution Network Leakage Rate	City Size Installed Infrastructure Open or closed pipes Pipe material			
Capacity to Use	Demand from Environment Demand from Society Accessibility of Water Affordability of Water Availability of Water	Perculation Evapotranspiration Domestic Demand Nondomestic Demand	Hemisphere Latitude Geology Topography Land Use Change Population Per Capita Domestic Use Economic Size Water Intensity of Economy	Geology Land Use Irradiance Temperature Day Length Household Size Household Services Technology Affordability of Water Type of Economy Technological Efficiency		
Capacity to Expand	Technology Sociopolitical support Finances	Type of supply, quality of supply, ease of access to supply Political geography				
Capacity to Maintain	System Stability Vulnerability to change System Complexity	Capacity of system to absorb shock	Unused Capacity Redundancy Socio-political support Disaster management plans	Financial, political, material, technical capacity and support		
Capacity to Manage	Financial capacity to manage Technical capacity to manage Governance capacity to manage	Socio-political support, level of incompetency, speed of decision-making				

Figure A-8: Summary of variables and processes pertaining to water scarcities.

Table A.4: Comparison of some system management metrics

Type of variable or indicator	Milman[19]	Simonović[16]	Madani[73]	Winz[38]	Stave[72]
Supply variables	Un-used supply Un-used capacity Percentage protected water sources Water quality Water system losses Governance capacity Sociopolitical support Financial capacity Savings Technical capacity	Water supply Water stock Precipitation Available groundwater Pollution Evaporation from groundwater and surface water	Water supply Water withdrawal Available groundwater Available surface water Pollution rate Evaporation from groundwater and surface water Legislation and policy levels Enforcement and administrative effort Available funding	Total water supply Perceived excess capacity Available groundwater Available surface water Pollution Evaporation from reservoirs	Total water supply Water withdrawn Other supply Available surface water Evaporation from reservoirs
Demand variables	System redundancy Population Total water consumption Per capita consumption Changes in water use patterns Cost of water to user Percentage of population with access Number of hours service per day Percent of supply points functioning Distance from source Infrastructure breakdown Climate change Natural and human induced disasters Political pressures Changing regulatory standards Supply capture by other users Financial risks	Population Water use Water per person Industrial water demand Water input per industrial output Industrial capital Agricultural demand Water input per food output	Population Water demand Per capita domestic water demand Residential water demand Municipal water demand Industrial water demand Per capita industrial water demand Population growth rate Agricultural water demand Per capita agricultural water demand	Water users and polluters Total water demand Per capita water use Residential water demand Nonresidential water demand	Population Total water demand Per capita residential water demand Residential water demand Nonresidential water demand Nonresidential per capita water demand Immigrations and emigrations
System stressors			Water resources sustainability index	Water tension	

A.3.2 Model Equation Listing

(001) Acceptable Cost of Water to Households= IF THEN ELSE(Proximity of Average Domestic Consumption to the Floor_i, Threshold Proximity , Maximum Acceptable Fraction of Household Budget for Water to Households, Expected Fraction of Household Budget for Water)*Average Household Income Units: Dollar/(Year*Household) As the expected fraction of household budget for water goes up, the acceptable cost of water to households goes up beyond what it would be otherwise. As average household income goes up, the cost of water to households also goes up.

(002) Achievable Reduction in Household Consumption= MAX(Achievable Reduction in Household Consumption due to Affordability,Achievable Reduction in Household Consumption from Availability) Units: m3/(Year*Household)

(003) Achievable Reduction in Household Consumption due to Affordability= IF THEN ELSE(Ratio of Actual to Acceptable Cost_i>1, Average Household Water Intensity /Ratio of Actual to Acceptable Cost, 0)*Elasticity of Reduction in Household Consumption to Budget (Ratio of Actual to Acceptable Cost) Units: m3/(Year*Household)

(004) Achievable Reduction in Household Consumption from Availability= Available Water Shortfall*Elasticity of Household Reduction to Availability (Relative Water Availability) Units: m3/(Year*Household)

(005) Actual Cost of Water to Households= Actual Domestic Use*Domestic Unit Price Units: Dollar/(Year*Household)

(006) Actual Domestic Use= Relative Water Avail-

ability*Average Household Water Intensity Units: m3/(Year*Household)

(007) Actual ET Fraction= Normal ET Fraction*Elasticity of ET to Temperature(Temperature Adjustment) Units: 1 Actual ET fraction adjusts the normal ET fraction for changes in temperature. This variable is mainly used for the climate scenario calculations but may also be used in other scenarios and calibrations. The use of temperature and ET in cities for which the ET and temperature vary more widely throughout the year should be considered in adapting this model for future scenarios.

(008) Actual Fraction of Household Budget for Water= Actual Cost of Water to Households/Average Household Income Units: 1 The actual fraction of the household budget for water is the cost of water to households divided by household income.

(009) Actual GDP= Economic Productivity*Effect of Water Availability on GDP Units: Dollar/Year

(010) Actual Production Capacity of Infrastructure= Infrastructure Production Capacity+Difference in Actual and Normal Production Capacity of Catchment Units: m3/Year

(011) Actual Production Capacity of Installed Catchment Area= Normal Production Capacity of Installed Catchment Area*Fractional Precipitation Adjustment Pulse Units: m3/Year
IF THEN ELSE (Total Installed Infrastructure_i,Normal Production Capacity of Installed Catchment Area,Infrastructure Production Capacity*(Fractional Precipitation Adjustment Pulse-1), Normal Production Capacity of Installed Catchment Area*Fractional Precipitation Adjustment Pulse)

(012) Actual Reduction= MIN(Achievable Reduction in Household Consumption,Maximum Reduction to Household Water Intensity) Units: m³/(Year*Household) Actual Reduction is the actual reduction of household water intensity that can be achieved at any given time.

(013) Actual Reduction in Economic Intensity= MIN(Max Outflow to Economic Intensity, Elasticity of Economic Water Intensity to Pressure to Reduce (Economic Pressure to Reduce Economic Intensity of Water)*Desired Water Intensity of Economy Reduction /Time to Adjust Water Intensity of Economy) Units: m³/(Dollar*Year)

(014) Actual Yearly Precipitation Input= Precipitation Input*(1-Actual ET Fraction)*Precipitation Collection Efficiency *CF Volume to Area Units: m³/(Year*Hectare) Average precipitation input per unit catchment area.

(015) Affordability of Operation= Budget Spent on Operation/Cost of Operation Units: dmn1

(016) Annual Hours Worked= 2000 Units: Hour/Year Average Hours worked per year for a typical full-time worker. Included to allow for augmenting of Production based on worker time-commitment. Baseline of 2,000 hours typical for an American worker (50 weeks *40 hours/week). Singaporeans may work different hours but this approximation should cancel out since ultimately the Labor Productivity was derived from data and the assumption that workers work 2000 hours a year. At time t = 2010, for scenario testing, Labor Intensity of Production is initialized at 1.22*1^-5, the last value in the data input sheet. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'AR5')

(017) Appreciation of PUB Capital= Normal Frac-

tional Appreciation*PUB Capital Units: Dollar/Year

(018) Available Water Shortfall= MAX(0, (1-Relative Water Availability)*Average Household Water Intensity) Units: m³/(Year*Household)

(019) Average Household Income= Economic Productivity/Number of Households*Trickledown Effect of GDP Units: Dollar/(Year*Household)

(020) Average Household Size= 4 Units: Person/Household This variable represents a change in the average number of people per households, which is related to affluence, average age of the population, number of people working, and housing availability. Since housing availability and the age of the population is outside the scope of this thesis, average household size is an input variable whose change over time is considered exogenously, even though it is really an endogenous variable. Future iterations of the model could consider the model independently; however, since it is potentially a policy variable for Singapore it is not completely unreasonable to consider it exogenously. The values in the data table are derived from information on the number of households and population. The accuracy of the data on number of households is uncertain. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'H5'). Assume for scenario testing that household size is constant for scenario runs, though this could change.

(021) Average Household Water Intensity= INTEG (Inflow to Household Water Intensity-Outflow from Domestic Demand, 252) Units: m³/Household/Year Average household water use. 3000L/person/year *4 people/household =12000L/household/year, 1000L/m³—*i* 12 m³/household/year. This variable assumes no floor

to consumption. The Maximum Value should be around 100 m³/household per year...more than that definitely doesn't make sense. The minimum value should be the floor to demand. 164 m³/year is calculated domestic demand. Reported is 95. By 2010, the average household water intensity is 252.

(022) Average Infrastructure Cost Increase= 1+STEP(1,Cost Exponential Growth Time)*(EXP(Cost Exponential Growth Rate*Time)-1)+STEP(1,Material and Energy Cost Volatility Start Time)*RANDOM NORMAL (-4 ,4 , 0 , Material and Energy Cost Volatility Standard Deviation, Material and Energy Cost Volatility Noise Seed) Units: Dimensionless The test input can be configured to generate a step, pulse, linear ramp, exponential growth, sine wave, and random variation. The initial value of the input is 1 and each test input begins at a particular start time. The magnitudes are expressed as fractions of the initial value.

(023) Average Storage Volume per Unit Storage Area= 41000 Units: m³/Hectare There are 10000m³ in a hectare. In 1968, storage capacity was 2.8E6 m³. So assume that in 1960, storage capacity was 2E6m³. Then, storage area in 1960 would be 2E2 Hectares. So Average Storage Volume per Unit Storage area is 41000 (ratio of 4 to 1 if area were in m² instead of hectares). GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'AD5')

(024) Average Water Intensity of Economy= INTEG (Inflow to Economic Water Intensity- Outflow to Economic Water Intensity, 0.003) Units: m³/Dollar In 1960, the water intensity of the economy is roughly .025. By 2010, it has decreased to .001. In the model scenario it decreases to .0028.

(025) Base Water Tariff= 0.3 Units: Dollar/m³ Initially the Water Tariff is \$0. Water Tariff is introduced in the Year 1990. In 2010, the base water tariff was 0.3. This could be modeled as a step input because the water tariff increased immediately.

(026) Budget for Infrastructure= IF THEN ELSE (Budget Remaining after Maintenance;Cost of Current Expansion ,Cost of Current Expansion, Budget Remaining after Maintenance) Units: Dollar/Year

(027) Budget Remaining After Depreciation= Outflow from PUB Capital-Depreciation of PUB Capital Units: Dollar/Year

(028) Budget Remaining after Maintenance= Budget Remaining after Operation-Budget Spent on Maintenance Units: Dollar/Year

(029) Budget Remaining after Operation= Budget Remaining After Depreciation-Budget Spent on Operation Units: Dollar/Year

(030) Budget Spent on Maintenance= IF THEN ELSE (Budget Remaining after Operation;Maintenance Cost of Production , Maintenance Cost of Production, Budget Remaining after Operation) Units: Dollar/Year

(031) Budget Spent on Operation= IF THEN ELSE(Budget Remaining After Depreciation;Cost of Operation, Cost of Operation , Budget Remaining After Depreciation) Units: Dollar/Year

(032) Capacity for Domestic Water Intensity Growth= MAX(0, (Maximum Acceptable Cost of Water to Households-Actual Cost of Water to Households)) Units: Dollar/(Year*Household) When Actual is greater than acceptable, affordability is less than one, and when the reverse is true it is greater than one.

(033) Capital Elasticity= 0.33 Units: dmnl Pro-

duction Elasticity to Fixed Capital, assumed to be 0.33, Based on Hall1999, p89. (alpha). Capital Elasticity is a constant and is not used as a dynamic input here.

(034) Catchment Area Adjustment for Johore= (Step Switch*STEP(Cost Step Height,Cost Step Time)+Ramp Switch*RAMP(Cost Ramp Slope ,Cost Ramp Start Time,Cost Ramp End Time))*Switch for Johore Catchment Area Units: 1 Adjustment for catchment area when johore disappears.

(035) Catchment Area per Unit Infrastructure= 1/Normal Yearly Precipitation Input Units: Hectare/(m3/Year) Ratio of Catchment Area of Unit Storage Area. In datainput-04122011.xls, 6 is the average value.GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'AC5'). 6

(036) CF Celsius= 1 Units: C This variable just adds units of Celsius to the temperature adjustment.

(037) CF Economic Capital= 1 Units: dmnl/Dollar CF Economic Capital is a conversion factor that cancels out the units of Economic Capital in the equation for Economic Productivity so that Vensim doesn't return an error message in the units.

(038) CF Economic Productivity= 1 Units: Dollar/Year CF Economic Productivity is a conversion factor that adds the units of Human Capital back into the equation for Economic Productivity so that Vensim doesn't return an error message in the units.

(039) CF Human Capital= 1 Units: Year CF Human Capital is a conversion factor that cancels out the units of Human Capital in the equation for Economic Productivity so that Vensim doesn't return an error message in the units.

(040) CF Volume to Area= 10000 Units: m3/(m*Hectare) converts volume to m3

(041) Change in Infrastructure Production Capacity due to Johore= Johore Initial Catchment Area Hectares*Normal Yearly Precipitation Input Units: m3/Year

(042) Change to Domestic Unit Price= Net Desired Price Increase*Net Pressure on Price Units: Dollar/m3/Year

(043) ChangeInHistorical Cost per Unit Infrastructure= (PerceivedCost per Unit Infrastructure - Historical Cost per Unit Infrastructure) / Duration Over Which to Calculate PUB Capital Units: Dollar/(Year*m3)

(044) ChangeInHistorical Domestic Demand= (Perceived Domestic Demand - Historical Domestic Demand) /

Durationfor Calculating Demand Units: m3/(Year*Year)

(045) ChangeInHistorical Economic Demand= (Perceived Water Demand of Economy - Historical Economic Demand) / Durationfor Calculating Demand Units: m3/(Year*Year)

(046) ChangeInHistorical Fractional Appreciation Rate= (PerceivedFractional Appreciation Rate - Historical Fractional Appreciation Rate)/Duration Over Which to Calculate PUB Capital Units: dmnl/Year/Year

(047) ChangeInHistorical PUB Capital= (PerceivedPUB Capital - Historical PUB Capital) / Duration Over Which to Calculate PUB Capital Units: Dollar/Year

(048) Construction Completion= MIN(Infrastructure Under Construction/Minimum Infrastructure Construction Time , Infrastructure Affordable) Units: m3/(Year*Year) Infrastructure Under Construc-

tion is equal to the infrastructure ordered. The rate at which infrastructure is completed depends on the typical construction completion time.

(049) Cost Exponential Growth Rate= 0.005 Units: 1/Year The exponential growth rate in the input.

In addition to cost increase due to material complexity, assume that there is inflation at 5% per year.

(050) Cost Exponential Growth Time= 0 Units: Year The time at which the exponential growth in the input begins. Assume that inflation at 5% a year begins in the year 2010.

(051) Cost of Current Expansion= Infrastructure Under Construction*Unit Cost of Infrastructure Expansion/Minimum Infrastructure Construction Time Units: Dollar/Year

(052) Cost of Operation= Financial Intensity of Operation*Infrastructure Production Capacity Units: Dollar/Year

(053) Cost of Proposed Expansion= MAX(0, Infrastructure in Planning)*Unit Cost of Infrastructure Expansion Units: Dollar

(054) Cost Ramp End Time= 50 Units: Year The end time for the ramp input; in this case it is 50 years, ending in 2060, the year of the treaty. This variable is used for scenario runs.

(055) Cost Ramp Slope= 2.7/50 Units: 1/Year The slope of the linear ramp in the input. Assume that over 50 years the cost of infrastructure and operation is gradually increased to 110% of the cost in 2010 by 2060, which is 10%/50 years = .2%/year.

(056) Cost Ramp Start Time= 0 Units: Year The time at which the ramp in the input begins. Assume the cost ramp begins in 2010.

(057) Cost Step Height= 2.7 Units: dmnl The height of the step increase in the input. Assume that the cost step associated with Johore is 115%

of cost in 2010.

(058) Cost Step Time= 50 Units: Year The time at which the step increase in the input occurs. Should occur in year 2060, or 50 years from the beginning of the simulation.

(059) Current Revenue Shortfall= MAX(0, Desired Revenue-Total Revenue) Units: Dollar/Year

(060) Depreciation of PUB Capital= Normal Fractional Depreciation*PUB Capital Units: Dollar/Year

(061) Desired Capital Buffer= Minimum Capital Residence Time Units: Year

(062) Desired Capital Stock= Total Cost of Water to Utility*Desired Capital Buffer Units: Dollar

(063) Desired Discharge Fraction= 0.01 Units: dmnl

(064) Desired Domestic Price due to Current Revenue Shortfall= MAX(0, Current Revenue Shortfall/Minimum Capital Residence Time/(Total Domestic Sales +Ratio of Nondomestic to Domestic Unit Price*Total Nondomestic Sales)) Units: Dollar/(m3*Year)

(065) Desired Domestic Price Increase= MAX(Desired Domestic Price due to Current Revenue Shortfall,Desired Increase in Domestic Price due to Projected Revenue Shortfall) Units: Dollar/(m3*Year)

(066) Desired Fraction Population Working= 0.53 Units: dmnl Fraction of the population working represents the fraction of the population of working age who are interested in being employed. It is not the actual number of people employed at any time. It is a function of relative affluence and age especially. The fraction of population working in 1960 is 0.33 and by 2010 it is 0.53. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' ,

'Q5'). Assume that for the scenario testing, the initial value is 0.53

(067) Desired Increase in Domestic Price due to Projected Revenue Shortfall = MAX(0, Projected Shortfall in Revenue/ForecastHorizon for Projecting PUB Capital /(Projected Domestic Demand+Ratio of Nondomestic to Domestic Unit Price*Projected Economic Demand)) Units: Dollar/(m3*Year)

(068) Desired Increase in Future Water Supply= Shortfall in Future Supply/Natural Residence Time Units: m3/Year The desired increase in future water supply is equal to the shortfall divided by the residence time of the system.

(069) Desired Increase in Storage Volume Area= Shortfall in Storage Volume/Average Storage Volume per Unit Storage Area Units: Hectare

(070) Desired Increase in Urbanized Land= Desired Urbanization Rate*Planning Period Units: Hectare The Desired Increase in Urbanized Land is the fractional change in urbanized land (normal) multiplied by the planning period.

(071) Desired Infrastructure Order Rate from Expansion= IF THEN ELSE(Relative Capital Availability $_t=1$, Proposed Catchment Area Expansion , 0)/Time to Increase Infrastructure in Planning Units: m3/Year/Year Infrastructure Order Rate depends on the relative capital availability at some time. If capital availability is low enough to not meet current demand, then no new infrastructure will be ordered.

(072) Desired Maximum Household Water Intensity= 240 Units: m3/Household/Year The base household water intensity reflects the fact that there is a price premium for water consumption above this baseline value. In 2010 the value was 240

m3/household/year. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'AS5').

(073) Desired Natural Discharge= Desired Discharge Fraction*Water Production Units: m3/Year

(074) Desired Pressure Increase due to current consumption overshoot= MAX(0, Normalized Overshoot of Domestic Use-1) Units: dmnl

(075) desired pressure increase due to future consumption overshoot= MAX(0, Normalized Projected Domestic Demand Overshoot-1)/Number of Households Units: dmnl

(076) Desired Price Increase from Consumption Overshoot= MAX(Desired Price Increase from Current Consumption Overshoot,Desired Price Increase from Future Consumption Overshoot) Units: Dollar/(Year*m3) This is the policy lever applying financial pressure to water consumers to encourage leveling demand.

(077) Desired Price Increase from Current Consumption Overshoot= Domestic Unit Base Price*Desired Pressure Increase due to current consumption overshoot /Unit Year Units: Dollar/(Year*m3)

(078) Desired Price Increase from Future Consumption Overshoot= Domestic Unit Base Price*desired pressure increase due to future consumption overshoot /ForecastHorizon for Projecting Demand Units: Dollar/(Year*m3)

(079) Desired Revenue= Desired Capital Stock/Minimum Capital Residence Time Units: Dollar/Year

(080) Desired Storage Volume= Water Resources-Desired Natural Discharge*Natural Residence Time Units: m3

(081) Desired Urbanization Rate= Fractional Urbanization Rate*Urbanized Land Units:

- Hectare/Year
- (082) Desired Water Coverage= 1 Units: Year
- (083) Desired Water Intensity of Economy Reduction= Normalized Economic Intensity of Water*Normal Desired Reduction*Economic Pressure to Reduce Economic Intensity of Water /Nondomestic Unit Price Units: m3/Dollar
- (084) Deteriorated Infrastructure= INTEG (Infrastructure Deterioration-Maintenance, Normal Deterioration Rate*Infrastructure Production Capacity*Unit Year) Units: m3/Year Infrastructure Production Capacity*Normal Deterioration Rate
- (085) Difference in Actual and Normal Production Capacity of Catchment= Actual Production Capacity of Installed Catchment Area-Normal Production Capacity of Installed Catchment Area Units: m3/Year
- (086) Domestic Collection Efficiency= 0.95 Units: dmnl
- (087) Domestic Unit Base Price= INTEG (Change to Domestic Unit Price, 1.17) Units: Dollar/m3 The domestic unit price in 1960 was 0.16 dollar/m3, increasing after that. In 2010, it was 1.17.
- (088) Domestic Unit Price= Domestic Unit Base Price+Water Tariff Units: Dollar/m3 The domestic unit price is the base unit price adjusted for water tariffing and normalized consumption.
- (089) Duration Over Which to Calculate PUB Capital= 15 Units: Year This is the time over which to calculate the trend. Should be related to the desired projection, although that is not always the case.
- (090) Durationfor Calculating Demand= 30 Units: Year This is the time over which to calculate the trend. Should be related to the desired projection, although that is not always the case. 15 years. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'B15')
- (091) Economic Capital= INTEG (Net Change in Economic Capital, 7*10^11) Units: Dollar Industrial Capital, as calculated by Noel, is 3200 Million Dollars in 1960, and by 2010 has risen to the 700 billion dollars. GDP is 6.6E9 \$\$/Year in 1960, and has grown to 200E9 \$\$/Year by 2007.
- (092) Economic Pressure to Reduce Economic Intensity of Water= Elasticity of Pressure to Reduce Economic Water Intensity to Water Intensity (Normalized Economic Intensity of Water) Units: 1 If Actual Economic Intensity of Water \geq Desired Economic Intensity of Water, the Pressure to Reduce the Economic Intensity of Water \geq 1. Then the desired reduction in economic water intensity \leq 1. How does water availability affect the pressure to reduce? If water availability is very low, people will be willing to pay twice as much as the current price, and then the pressure will be a negative pressure. If Acceptable \geq Actual, then the Pressure to Reduce = 0. If Actual \geq Acceptable, then pressure will be \geq 0.
- (093) Economic Productivity= ((Unitless Economic Capital)^ Capital Elasticity) *((Labor Productivity *Human Capital)^ Labor Elasticity)*CF Economic Productivity Units: Dollars/Year Production is the Gross Domestic Product, measured in Dollars per Year. Equation adapted from Hall1999, p87. (Y)
- (094) Effect of Economic Prosperity on Population Inflow= Elasticity of Population Inflow to Job Availability(Job Availability) Units: dmnl
- (095) Effect of GDP on Economic Growth= Elasticity of Economic Capital Inflow to Normalized GDP(Normalized GDP Productivity) Units: dmnl

(096) Effect of Job Availability on Population Outflow= Elasticity of Population Outflow to Job Availability(Job Availability) Units: dmnl

(097) Effect of Johore Catchment Removal on Infrastructure Construction Capacity = $(1/\text{TIME STEP})*\text{PULSE}(50, \text{TIME STEP})*\text{Switch for Johore Catchment Area}$ Units: dmnl This reduces the infrastructure capacity due to the phasing out of Johore Catchment.

(098) Effect of Relative Domestic Water Availability on Population Outflow= Elasticity of Population Outflow to Relative Water Availability(Relative Water Availability) Units: dmnl Since the Relative Availability of Domestic Water is defined on the interval of (0,1), the Elasticity of Population Outflow to Relative Water Availability should never go above or below the table function.

(099) Effect of Water Availability on GDP= Elasticity of GDP to Relative Socioeconomic Availability(Relative Water Availability) Units: dmnl

(100) Elasticity of Capital Outflow to Availability([0,0)-(5,1)], (0,0), (0.3,0.25), (0.7,0.7), (1,1), (2,1), (5,1)) Units: dmnl Elasticity of Capital Outflow to Availability of Capital Outflow.

(101) Elasticity of Economic Capital Inflow to Normalized GDP([(0,0)-(1,1)], (0,0), (0.25,0.5), (0.4,0.75), (0.65,1), (1,1)) Units: dmnl Elasticity of Economic Capital Inflow to Normalized GDP Productivity. When Actual GDP falls below Economic Productivity, then when the threshold of 0.65 is reached, net economic growth should be lower than it would be otherwise. The maximum Normalized GDP is 1.

(102) Elasticity of Economic Water Intensity to Pressure to Reduce([(0,0)-(10,1)],(0,0.25), (0.25,0.25), (1,0.25), (2.25,0.4), (4.25,0.7), (

5.8,0.75), (9,0.8), (10,0.8)) Units: dmnl Elasticity of Water Intensity Reduction to Desired Reduction. As Pressure to Reduce is very high, then Actual reduction should approach desired reduction.

(103) Elasticity of ET to Temperature([(-10,0)-(10,4)], (-10,0.8), (10,1.5)) Units: dmnl The Elasticity of ET to Temperature is an input curve representing how evapotranspiration demand from the environment changes with temperature. This elasticity aggregates a number of physical processes that could be disaggregated in future runs of the model. As such it is not the most precise representation of how ET demands change with temperature. This elasticity is formulated relative to a reference temperature, which we take to be the average temperature experienced in Singapore. However, please note that since ET is a function not only of temperature but also of other aspects of climate including irradiance, etc., that this is an oversimplification and future iterations may prefer to include sensitivities to other variables. The input is the normalized average yearly temperature, which is assumed to vary with a standard deviation of no more than plus or minus 10 degrees C, which is rather a lot, and may be a larger range than necessary. The output the this table function could be in m/year, but since the formulation for precipitation input adjusts actual precipitation for ET demand, ET demand is given as a fraction of the precipitation input. For purposes of multiple of normal ET requirements. The temperature of Singapore is normally high; around 30. It is tropical and wet and the evapotranspiration measurements are assumed to be close to the theoretical maximum under those conditions. The rainfall input to Singapore is 2.25 m/year. Normal ET is about half

of that. Assume that maximum ET may get up to 75% (or $75/50 = 3/2 = 150\%$ of normal ET) of that when the average temperature increases by 10 C to 40C and when the temperature drops to 20C, the ET demand is 40% of total, or $40/50 = 80\%$ of normal ET.

(104) Elasticity of GDP to Relative Socioeconomic Availability([(0,0)-(1,1)], (0,0.25), (0.2,0.25), (0.75,1), (1,1)) Units: dmnl Elasticity of GDP to Water Availability. As Water Availability goes down, GDP will be affected. If the fraction of water available is one, then $GDP = GDP$. However, if Water Availability Drops below 75%, assume that GDP will drop, also, down to 25%.

(105) Elasticity of Growth in Economic Water Intensity to Affordability([(0,1)-(10,0)], (0,1), (0.1,1), (0.2,1), (0.5,0), (1,0), (10,0)) Units: dmnl Elasticity of Growth in Economic Water Intensity due to 2nd Law. Assume a 0.5% growth per year. As Pressure to Reduce Economic Intensity of Water is High, then the Growth will go down to zero. If Pressure to Reduce is low, then it will be as normal.

(106) Elasticity of Household Budget to Proximity to Floor([(0,0)-(2,1)], (0,0.025), (0.075,0.025), (0.125,0.03), (0.15,0.035), (0.25 ,0.075), (0.5,0.25), (0.75,0.5), (1,1), (1.5,1), (1.8,1), (2,1)) Units: dmnl Elasticity of Acceptable Fraction of Budget to the Proximity to the Floor. As the Proximity to the floor approaches one, then the acceptable fraction of budget for household water goes up beyond what it would be otherwise, with a maximum fraction of the budget to be $0.4 * \text{household income}$. When the consumption is greater than 2 times the floor, then the acceptable cost of water to households is equal to the expected fraction of the household budget for water. This represents the fact that people are less

likely to reduce household use and are more willing to pay for water when they are not consuming very much.

(107) Elasticity of Household Reduction to Availability([(0,0)-(1,1)], (0,0.5), (0.25,0.5), (0.5,0.75), (0.75,1), (1,1)) Units: dmnl As the Relative Water Availability goes up relative to demand, the shortfall in water resources will go down, but and the desired reduction will go up. However, the achievable reduction in household water intensity should go up. The Elasticity is formulated as a linear elasticity that is only active on a certain range of Relative Water Availability. The minimum achievable household reduction is a reduction by 25% of the shortfall. The maximum achievable reduction is 100%, which occurs when water availability is greater than 90% of demand.

(108) Elasticity of Household Water Intensity Growth to Availability([(0,0)-(1,1)], (0,0), (0.25,0), (0.85,1), (1,1)) Units: dmnl Table for the Effect of Water Availability on Growth in Demand. When Water Availability is 1, demand growth should be normal. When avl falls below demand, growth should quickly taper off, faster than availability. When Water Availability is zero, then growth in demand should be zero. Water demand growth should be zero up until water availability is at least 25% of demand.

(109) Elasticity of Household Water Intensity Growth to Floor([(0,0)-(3,1)], (0,0.001), (0.1,0.1), (0.25,0.25),(0.5,0.4), (1,0.65), (3 ,1)) Units: dmnl As Proximity to the Floor Goes up, Growth Should approach one. As consumption moves away from the floor, growth should slow.

(110) Elasticity of Infrastructure Expansion Financial Intensity to Normalized Catchment Area (

$[(0,0)-(6,40)]$, (0,1), (0.016,2), (0.018,2.1), (0.8,2.1),
 (1.1,2.7), (1.2 ,9.4), (1.3,40), (6,40)) Units: dmnl

Elasticity of Infrastructure Expansion Financial Intensity is a table function that adjusts the financial intensity upwards as the installed infrastructure increases. The levels of the table funciton depend on the local carrying capacity of the region for a particular type of infrastructure. The numbers in this table funciton are calculated from the graphs of capital expenditure per unit sold graphed against normalized catchment area.

(111) Elasticity of Maintenance Financial Intensity to NPC($[(0,0)-(20,20)]$, (0,0), (0.06,2), (1,2),
 (1.1,10), (1.2,10), (2,10), (6,10), (10,13), (12,17),
 (20,20)) Units: dmnl As in the table function.

(112) Elasticity of Operation Financial Intensity to NPC($[(0,0)-(20,7)]$, (0,0.4), (0.04,1), (0.06,1.3),
 (1,1.3), (1.1,1.8), (1.2,2), (1.21,4), (6,4), (10,5),
 (20,7)) Units: dmnl Financial Intensity of Operation changes with the type of technology used. The type of technology used is captured in the Normalized Infrastructure Production Capacity variable.

(113) Elasticity of Population Inflow to Job Availability($[(0,0.5)-(2,2)]$, (0,0.5), (0.1,0.5), (0.75,1),
 (1,1), (1.25,1), (1.6,1.7) , (1.8,2), (2,2)) Units: dmnl Elasticity of Population Increase to Job Availability. If Job Availability is 1 or greater than one, then population will increase. If Job Availability is less than 1, the effect should be just one.

(114) Elasticity of Population Outflow to Job Availability($[(0,0)-(2,6)]$, (0,2), (0.1,2), (0.25,2), (0.4,2),
 (0.75,1), (1,1), (1.25, 1), (1.75,0.5), (2,0.5)) Units:
 dmnl Elasticity of Population Outflow to Job Availability. If Job Availability is less than one, then there should be a positive effect on population outflow, similar to how it is for water availability. How-

ever, Job Availability will max out sooner than wa-
 ter availability.

(115) Elasticity of Population Outflow to Rela-
 tive Water Availability($[(0,0)-(1,6)]$, (0,5), (0.1,5),
 (0.25,5), (0.3,4.8), (0.6,3), (0.75,1.5), (0.8,1), (1,1))
 Units: dmnl Elasticity of Population Outflow to Rela-
 tive Availability of Domestic Water. If Avail-
 ability is One, then there will be no effect on the
 outflow from population, so the effect should be
 one. If Availability is less than one, the effect on
 outflow should increase, up to a maximum at 25%
 availability, at which time the outflow from popu-
 lation should be five times as high as it would be
 otherwise.

(116) Elasticity of Pressure to Current Shortfall(
 $[(0,0)-(1,1)]$, (0,0), (0.15,0.095), (0.25,0.25), (0.5,1),
 (0.7,1), (1,1)) Units: dmnl Elasticity of Pressure
 to Current Shortfall. Pressure to Current shortfall
 should be higher than for future shortfall.

(117) Elasticity of Pressure to Future Shortfall(
 $[(0,0)-(10,3)]$, (0,0), (0.25,0.05), (0.5,0.1), (1,0.5),
 (2.25,0.9), (3,1) , (5,1), (10,1)) Units: dmnl Elas-
 ticity of Pressure to Future Shortfall. If Future
 Shortfall is higher, then the Price Should be Higher
 than it is otherwise. However, the pressure should
 be lower than it is for a current shortfall.

(118) Elasticity of Pressure to Reduce Economic
 Water Intensity to Water Intensity ($[(0,0)-(0.1,10)]$,
 (0,3.5), (0.005,4), (0.01,6.25), (0.0125,7),
 (0.015,7.5), (0.025,8.5), (0.1,10)) Units: dmnl Elas-
 ticity of Pressure to Reduce Economic Water Inten-
 sity to Water Intensity (Normalized). Let Water
 Intensity Max = 2, and MIN =0. As Water Inten-
 sity is very small, the pressure to reduce decreases
 to 10% of the normal value. When Normalized Wa-
 ter Intensity is 1, then Pressure is 1.

(119) Elasticity of Pressure to Reduce Price to Domestic Affordability([(0,0)-(2,1)],(0,0), (0.1,0), (0.3,0.085), (0.5,0.25), (0.75,0.95), (1,1) , (2,1)) Units: dmnl As the Ratio of Actual to Acceptable Cost approaches one, the pressure to increase price should increase.

(120) Elasticity of Pressure to Reduce Price to Economic Pressure([(0,0)-(3,1)], (0,0), (0.5,0.125), (1,0.5),(1.5,0.9), (2,1), (3,1)) Units: dmnl As the Pressure to Reduce Price is defined over zero to 10, its elasticity should be defined on the same interval. Pressure to Decrease Price should increase with Economic Pressure. Consider the bounds to be on zero to three (times the normal pressure). When the pressure is similar to the normal pressure, then the pressure to decrease price should be close to zero.

(121) Elasticity of Reduction in Household Consumption to Budget([(0,0)-(3,0.4)], (0,0), (0.5,0), (0.75,0), (1,0), (1.1,0.05), (1.25,0.1), (1.5,0.15), (2,0.2), (2.5,0.25),(3,0.25)) Units: dmnl As the ratio of actual to acceptable cost goes above one, then the reduction should be equal to the shortfall. As the ratio gets higher, the desired reduction should max out to a quarter of consumption. Below one the desired reduction should be zero.

(122) Elasticity of Water Consumption to Availability([(0,0)-(5,1)], (0,0), (0.3,0.25), (0.7,0.6), (1,1), (5,1)) Units: dmnl Elasticity of Water Outflow to Availability of Water Resource is an elasticity that controls the amount of water that can be consumed relative to the water stock. As the maximum outflow approaches socioeconomic demand, the desired outflow will be higher than the actual outflow.

(123) Elasticity of Water Tariff to Domestic In-

tensity([(0,0)-(10,2.5)], (0,0), (1,0), (1.8,0), (2,1), (10,1)) Units: dmnl Elasticity of Water Tariff to Domestic Intensity is a variable that adds an increased value to the base domestic price when average household use exceeds the base value.

(124) Expected Fraction of Household Budget for Water= $\text{INTEG}(\text{Net Change to Acceptable Fraction of Household Budget for Water}, \text{Actual Domestic Use} * \text{Domestic Unit Price} / \text{Average Household Income})$ Units: dmnl The expected fraction of the household budget for water reflects the lag time in what people are willing to pay for water. At the end of the model run it was .002.

(125) FINAL TIME = 80 Units: Year The final time for the simulation.

(126) Financial Intensity of Maintenance= Elasticity of Maintenance Financial Intensity to NPC(Normalized Catchment Area Equivalent)*Normal Financial Intensity of Maintenance*Average Infrastructure Cost Increase Units: Dollar*Year/m³

(127) Financial Intensity of Operation= Elasticity of Operation Financial Intensity to NPC(Normalized Catchment Area Equivalent +Catchment Area Adjustment for Johore)*Normal Financial Intensity of Operation *Average Infrastructure Cost Increase Units: Dollar/m³ Financial Intensity of Operation is the cost per m³ of water produced by infrastructure. This includes distribution costs. This is adjusted from the historical financial cost intensity of operation formulation to account for an estimation of cost increases that is formulated as a multiplicative factor.

(128) Floor to Household Consumption= Floor to Per Capita Consumption*Average Household Size Units: m³/(Year*Household)

(129) Floor to Per Capita Consumption= 5 Units: m³/Person/Year 50L/capita/day = 0.05m³/capita/day = 18.25 m³/capita/year

(130) ForecastHorizon for Projecting Demand= 50 Units: Year PUB Master Plans indicate that the utilities board and government looks 20-50 years into the future. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'BH5'). For scenario runs, assum 50 years.

(131) ForecastHorizon for Projecting PUB Capital= 30 Units: Year

(132) Fractional Precipitation Adjustment Pulse= Actual Yearly Precipitation Input/Normal Yearly Precipitation Input Units: 1 When Actual > Normal, then Infrastructure Production Capacity is Greater than 1.

(133) Fractional Urbanization Rate= 0.05 Units: dmnl/Year The rate at which land is urbanized and thus taken out of land potentially available for storage. From datainput-04122011.xls. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'AA5'). Assume .05 (5% reclamation) for scenario testing.

(134) FractionalTrend in Domestic Demand = (Perceived Domestic Demand - Historical Domestic Demand) / (Historical Domestic Demand *Durationfor Calculating Demand) Units: dmnl/Year

(135) FractionalTrend in Economic Demand= (Perceived Water Demand of Economy - Historical Economic Demand) /(Historical Economic Demand *Durationfor Calculating Demand) Units: dmnl/Year

(136) FractionalTrend in Fractional Appreciation= (PerceivedFractional Appreciation Rate - Historical Fractional Appreciation Rate)/(Historical Fractional Appreciation Rate *Duration Over Which to

Calculate PUB Capital) Units: dmnl/Year

(137) FractionalTrend in IUC= (PerceivedCost per Unit Infrastructure - Historical Cost per Unit Infrastructure)/(Historical Cost per Unit Infrastructure *Duration Over Which to Calculate PUB Capital) Units: dmnl/Year

(138) FractionalTrend in PUB Capital = (PerceivedPUB Capital - Historical PUB Capital) / (Historical PUB Capital *Duration Over Which to Calculate PUB Capital) Units: dmnl/Year

(139) Growth in Domestic Demand= Capacity for Domestic Water Intensity Growth*MIN(Elasticity of Household Water Intensity Growth to Availability (Relative Water Availability), Elasticity of Household Water Intensity Growth to Floor (Proximity of Average Domestic Consumption to the Floor))/Domestic Unit Price /Time to Grow Household Water Intensity Units: m³/(Year*Year*Household) Growth in Domestic Water Demand is a growth related to household affluence and limited by household income and water availability.

(140) Growth in Economic Water Intensity= Elasticity of Growth in Economic Water Intensity to Affordability(Economic Pressure to Reduce Economic Intensity of Water)*Average Water Intensity of Economy*Normal Growth in Economic Water Intensity Units: m³/(Dollar*Year) Growth in water intensity occurs unless people are actively working against it.

(141) Historical Cost per Unit Infrastructure= INTEG (ChangeInHistorical Cost per Unit Infrastructure, (Maintenance Cost of Production + Cost of Operation)/Infrastructure Production Capacity) Units: Dollar/m³ This can be initialized back in time such that it starts at a non-zero value.

(142) Historical Domestic Demand= INTEG (ChangeInHistorical Domestic Demand, 300*10^6) Units: m3/Year This can be initialized back in time such that it starts at a non-zero value. For sensitivity testing, initialized to Total Domestic Demand/Initial Historical Domestic Demand Fraction. For scenarios, socioeconomic demand is 300 million m3/year.

(143) Historical Economic Demand= INTEG (ChangeInHistorical Economic Demand, 300*10^6) Units: m3/Year This can be initialized back in time such that it starts at a non-zero value. For sensitivity testing, initialized at Total Economic Water Demand/Initial Historical Economic Demand Fraction. In 2010, the water demand is 300 million m3/year.

(144) Historical Fractional Appreciation Rate= INTEG (ChangeInHistorical Fractional Appreciation Rate, Normal Fractional Appreciation) Units: dmnl/Year This can be initialized back in time such that it starts at a non-zero value.

(145) Historical PUB Capital= INTEG (ChangeInHistorical PUB Capital, PUB Capital) Units: Dollar This can be initialized back in time such that it starts at a non-zero value.

(146) Human Capital= EXP(Return on Education) *Workforce *Annual Hours Worked*CF Human Capital Units: Person*Hour This is the total Human Capital input, adjusted for skill (education) of workers. (H)"

(147) Income from Government and Loans= MAX(0, Desired Revenue-Depreciation of PUB Capital-Total Revenue) Units: Dollar/Year Income from Government and Loans is a variable that represents the fact that for much of Singapore's history, the PUB operation has been supplemented

by costs offset by government.

(148) Increase to Infrastructure in Planning= MAX(0, Desired Infrastructure Order Rate from Expansion) Units: m3/(Year*Year)

(149) Inflow to Economic Water Intensity= Growth in Economic Water Intensity Units: m3/Dollar/Year Changing water intensity. Growth is mainly an entropy variable/affluence variable.

(150) Inflow to Household Water Intensity= Growth in Domestic Demand Units: m3/(Year*Year*Household)

(151) Inflow to Population= MIN(Net Inflow to Population, Maximum Inflow to Population) Units: Person/Year

(152) Inflow to PUB Capital= MAX(0,Appreciation of PUB Capital+Total Revenue+Income from Government and Loans) Units: Dollar/Year Assume that the inflow to water resources is equal to the Desired water production rate

(153) Inflow to Storage Area= Maximum Inflow to Storage Area Units: Hectare/Year

(154) Inflow to Water Resources= Water Production Units: m3/Year Assume that the inflow to water resources is equal to the Desired water production rate

(155) Infrastructure Affordable= Budget for Infrastructure/Unit Cost of Infrastructure Expansion Units: m3/(Year*Year)

(156) Infrastructure Deterioration= Infrastructure Production Capacity*Normal Deterioration Rate Units: m3/(Year*Year)

(157) Infrastructure in Planning= INTEG (Increase to Infrastructure in Planning-Infrastructure Order Rate, Initial Infrastructure in Planning) Units: m3/Year This stock represents the infrastructure that has been identified as needing to be

built. It is the infrastructure that is needed to meet shortfall or a future shortfall. However, after the shortfall has been identified, infrastructure construction does not begin; it must first be planned.

(158) Infrastructure Order Rate= MAX(0, Infrastructure in Planning/Planning Period) Units: m³/(Year*Year)

(159) Infrastructure Order Rate from Maintenance= Deteriorated Infrastructure/Time to Order Maintenance Units: m³/(Year*Year)

(160) Infrastructure Outflow due to Policy= Effect of Johore Catchment Removal on Infrastructure Construction Capacity *Change in Infrastructure Production Capacity due to Johore Units: m³/Year
When the switch for Johore Catchment Area is 1, then the infrastructure outflow is zero, and when it is zero the Johore catchment is permanently removed from the catchment area. This variable can also be adapted to look at responses to catastrophes.

(161) Infrastructure Production Capacity= INTEG (Construction Completion+Maintenance-Infrastructure Deterioration-Infrastructure Outflow due to Policy , 1.34*10⁹) Units: m³/Year
Should be initialized to some reasonable number. This is the amount of infrastructure required to produce a certain amount of water coming in. For now, initialize the production capacity at some value higher than the sales in 1960, which is 90,000 thousand m³/year.

(162) Infrastructure Under Construction= INTEG (Infrastructure Order Rate-Construction Completion, Initial Infrastructure Construction) Units: m³/Year Between 1960 and 1969, Infrastructure Increases by about 60 million m³/year.

(163) Initial Historical Domestic Demand Frac-

tion= 1.2 Units: dmnl Not sure what the historical domestic water demand on the books was, so assume that historic domestic demand depended mainly on the change in population. Historic population (change over 1957-1941 in Master Data.xls) was 1.6 times less than in 1960.

(164) Initial Historical Economic Demand Fraction= 1.2 Units: dmnl Not sure what the historical economic water demand on the books was, so assume that historic economic demand depended mainly on the change in economic activity. Data on that is also not in the current spreadsheet, so guess that historic demand was 1.6 times less than in 1960.

(165) Initial Infrastructure Construction= 0 Units: m³/Year For scenario testing, initialized at 1.8*10⁸. For sensitivity testing, initialized at zero.

(166) Initial Infrastructure in Planning= 0.5*10⁶ Units: m³/Year This input to this variable is the infrastructure that is in planning at t = 0. In the calibrated model, the Initial Infrastructure in Planning in the year 2010 was 9.3*10⁸. For sensitivity testing, initialized at the value of infrastructure constructed in the 15 years after 1960, 0.5*10⁶

(167) Initial Percent Land Area Urbanized= 0.4 Units: dmnl 0.4 From datainput-04122011.xls.

(168) INITIAL TIME = 0 Units: Year The initial time for the simulation.

(169) Initial Total Land Area= 70000 Units: Hectare 600km² = 600*10⁶ m². 1 hectare = 1*10⁴ m², so 600km² = 60000hectares. 58150 from datainput-04122011.xls

(170) Installed Catchment Area in Singapore= INTEG (Net Change in Installed Catchment Area, 2/3*Total Land Area) Units: Hectare The installed catchment area in Singapore at time t = 0 is around

at least 70/% of the island area. In 2010, the installed catchment in Singapore is two thirds of the island.

(171) Job Availability= Number of Jobs/Workforce Units: dmnl [0,3] If Number of Jobs \geq Workers, then Job Availability \geq 1, and people should be less likely to leave and more likely to come in. If Job Availability is \leq 1, the reverse is true. Job Availability should never go below zero but the maximum value is harder to define and should depend on historical data. Three times the number of jobs relative to workers seems like the maximum job availability.

(172) Johore Initial Catchment Area Hectares= 40000 Units: Hectare Assume that the initial catchment area of Johore is greater than half the island area of Singapore. 40000

(173) Labor Elasticity= 1 - Capital Elasticity Units: dmnl Production Elasticity to Labor, assumed to be 0.67, 1 - alpha, Based on Hall1999, p87. (1-alpha)

(174) Labor Intensity of Production= 1.22×10^{-5} Units: Person/(Dollar/Year) Number of workers required to produce a unit of GDP. The data input is derived by dividing GDP by the data on the number of workers in the economy. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'R5'). At time t = 2010, for scenario testing, Labor Intensity of Production is initialized at 1.22×10^{-5} , the last value in the data input sheet.

(175) Labor Productivity= 8.42 Units: 1/(Person*Hour) This is a Labor-Augmenting Productivity factor. This term is calculated based on known quantities for all other components of the Cobb-Douglas Production Function. Labor Productivity is considered to be the technology component of la-

bor productivity, since skill level (education) is already accounted for. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'S5'). For scenario testing Labor Productivity is initialized at its final value in the data sheet, or 8.42

(176) Maintenance= Budget Spent on Maintenance/Financial Intensity of Maintenance Units: m3/(Year*Year)

(177) Maintenance Cost of Production= Infrastructure Order Rate from Maintenance*Financial Intensity of Maintenance Units: Dollar/Year Financial Intensity of Maintenance is the cost per m3 of water produced by infrastructure. This includes distribution costs. This is adjusted from the historical financial cost intensity of operation formulation to account for an estimation of cost increases that is formulated as a multiplicative factor.

(178) Material and Energy Cost Volatility Noise Seed= 5 Units: dmnl Varying the random number seed changes the sequence of realizations for the random variable.

(179) Material and Energy Cost Volatility Standard Deviation= 0.1 Units: dmnl The standard deviation in the random noise. The random fluctuation is drawn from a normal distribution with min and max values of +/- 4. The user can also specify the random number seed to replicate simulations. To generate a different random number sequence, change the random number seed.

(180) Material and Energy Cost Volatility Start Time= 0 Units: Year The time at which the random noise in the input begins.

(181) Max Economic Water Intensity Reduction= 0.4 Units: dmnl/Year GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'BD5'). Assume 0.5 in 2010 and scenario runs.

(182) Max Outflow from Undeveloped Land= (Undeveloped Land-Policy Protected Land)/Planning Period Units: Hectare/Year Maximum Outflow from Unprotected Land reflects the fact that some land is protected by policy from being developed for urbanization or water infrastructure.

(183) Max Outflow to Economic Intensity= MAX(0, Max Economic Water Intensity Reduction*(Average Water Intensity of Economy *(1-Minimum Water Intensity of Economy))) Units: m3/(Dollar*Year)

(184) Maximum Acceptable Cost of Water to Households= Average Household Income*Maximum Acceptable Fraction of Household Budget for Water to Households Units: Dollar/(Year*Household)

(185) Maximum Acceptable Fraction of Household Budget for Water to Households = Elasticity of Household Budget to Proximity to Floor(Proximity of Average Domestic Consumption to the Floor)*Maximum Fraction of Budget for Water Units: dmnl

(186) Maximum Desired Domestic Demand= Desired Maximum Household Water Intensity*Maximum Desired Population/Average Household Size Units: m3/Year

(187) Maximum Desired Population= 8.5e+06 Units: Person The Maximum Desired Population is a value set by Singapore planners, who have more control than many city planners over how many people come to the city. It could also be modeled with a step increase at the time of the master plans. GET XLS DATA('datainput-04122011.xls', 'Sheet1' , 'A' , 'D5'). The data for this variable reflects the mental models of Singapore decision makers that were identified in their master

plans. The recent desired maximum population of Singapore is set at 8.5 million people. Assume that this is constant for the scenario runs.

(188) Maximum Fraction of Budget for Water= 0.1 Units: dmnl Assume that the maximum fraction of budget to be spent on water is 0.2

(189) Maximum Inflow to Population= (Maximum Desired Population-Population)/Unit Year Units: Person/Year

(190) Maximum Inflow to Storage Area= Max Outflow from Undeveloped Land*(1-Ratio of Demand for Land for Urbanization vs Storage) Units: Hectare/Year

(191) Maximum Inflow to Urbanized Land= Max Outflow from Undeveloped Land*Ratio of Demand for Land for Urbanization vs Storage Units: Hectare/Year

(192) Maximum Outflow to PUB Capital= PUB Capital/Minimum Capital Residence Time Units: Dollar/Year

(193) Maximum Outflow to Water Resources= Water Resources/Minimum Residence Time Units: m3/Year

(194) Maximum Reduction to Household Water Intensity= MAX(0, Average Household Water Intensity-Floor to Household Consumption) Units: m3/(Year*Household)

(195) Minimum Capital Residence Time= 1 Units: Year

(196) Minimum Infrastructure Construction Time= 4 Units: Year How long it will take to complete infrastructure currently under construction.

(197) Minimum Residence Time= 0.5 Units: Year Assume that the natural residence time of all the water in the socioeconomic system is on the order

of a year.

(198) Minimum Water Intensity of Economy= 0 Units: dmnl Assume that the floor is a value of economic water intensity for a highly service-based economy such as a banking center. Not sure of a reasonable value for this. I don't think this is an important variable so setting to zero.

(199) Natural Discharge= (Water Resources-Storage Volume of Infrastructure)/Natural Residence Time Units: m3/Year (Water Resources-Storage Volume of Infrastructure)/Minimum Residence Time

(200) Natural Residence Time= 2 Units: Year

(201) Net Change in Economic Capital= Net Change to Economy Units: Dollar/Year

(202) Net Change in Installed Catchment Area= MIN((Total Land Area-Installed Catchment Area in Singapore)/Minimum Infrastructure Construction Time , Construction Completion *Catchment Area per Unit Infrastructure) Units: Hectare/Year

(203) Net Change to Acceptable Fraction of Household Budget for Water= (Actual Fraction of Household Budget for Water-Expected Fraction of Household Budget for Water)/Time to Change Mental Model about Household Water Cost Units: dmnl/Year The net change to the expected fraction of household budget for water is given by the difference between the actual cost and the previous cost.

(204) Net Change to Economy= Economic Capital*Net Economic Growth Units: Dollar/Year

(205) Net Desired Price Increase= MAX(Desired Price Increase from Consumption Overshoot, Desired Domestic Price Increase) Units: Dollar/(m3*Year)

(206) Net Economic Growth= Effect of GDP on

Economic Growth*Normal Fractional Economic Growth Units: 1/Year

(207) Net Fractional Decrease to Population= Normal Fractional Decrease to Population*Effect of Job Availability on Population Outflow *Effect of Relative Domestic Water Availability on Population Outflow Units: 1/Year

(208) Net Fractional Increase to Population= (Normal Fractional Increase to Population)*Effect of Economic Prosperity on Population Inflow Units: dmnl/Year

(209) Net Inflow to Population= Net Fractional Increase to Population*Population Units: Person/Year

(210) Net Outflow to Population= Net Fractional Decrease to Population*Population Units: Person/Year

(211) Net Pressure on Price= Pressure to Increase Price/(1+Pressure to Decrease Price) Units: dmnl Net Pressure on price to increase and decrease it.

(212) Nondomestic Collection Efficiency= 0.95 Units: dmnl

(213) Nondomestic Unit Price= Domestic Unit Base Price*Ratio of Nondomestic to Domestic Unit Price Units: Dollar/m3

(214) Normal Desired Reduction= 0.125 Units: dmnl Assume that managers always want to see at least a 10% improvement.

(215) Normal Deterioration Rate= 0.0001 Units: dmnl/Year 0.01

(216) Normal Economic Pressure on Water Price Reduction= 4 Units: dmnl

(217) Normal ET Fraction= 0.5 Units: dmnl Normally ET is half of precipitation.

(218) Normal Financial Intensity of Infrastructure Expansion= 0.2 Units: Dollar/(m3/Year)

(219) Normal Financial Intensity of Maintenance= 0.028 Units: Dollar/(m³/Year) Set to the initial Capital Expenditure per unit sold.

(220) Normal Financial Intensity of Operation= 0.137 Units: Dollar/m³ In 1960 the operating cost per unit produced was 0.170 Dollar/m³. Assume that the operating cost is split 75-25 with maintenance and does not include infrastructure expansion. In fact, infrastructure expansion might be better modeled as a separate cost not attributable to the utilities.

(221) Normal Fractional Appreciation= 0.04 Units: dmnl/Year

(222) Normal Fractional Decrease to Population= 0.007 Units: dmnl/Year GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'F5') Average Outflow to Population is .009, as calculated from Data available in datainput-04122011.xls.

(223) Normal Fractional Depreciation= 0.01 Units: dmnl/Year

(224) Normal Fractional Economic Growth= 0.08 Units: dmnl/Year If Gross Fixed Capital Formation has an average of 0.11, and a median of 0.12, and we assume depreciation to be on the order of 0.05% a year, then a fractional increase to economy of 0.15 seems a reasonable assumption. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'L5'). For scenario modeling, the value is set to the value at t = 2010. For Normal Fractional Economic Growth, this value is .111

(225) Normal Fractional Increase to Population= 0.0325 Units: dmnl/Year GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'E5') Normal Inflow to Population is about .0284, as calculated in datainput-04122011.xls. Input as a dynamic input, in case more data is found.

(226) Normal Growth in Economic Water Intensity= 0.0001 Units: dmnl/Year Assume Water Inefficiency accumulates at 0.5% a year. This variable represents a growth in demand that arises from socioeconomic processes outside the scope of this thesis, including inefficiencies that arise in the use of water, waste due to availability, and increasing number of services that require water.

(227) Normal Production Capacity of Installed Catchment Area= Total Installed Catchment Area*MAX(0, (Normal Yearly Precipitation Input)) Units: m³/Year

(228) Normal Reclamation Rate= 0 Units: dmnl/Year From datainput-04122011.xlsx. Normal value is 0.004. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'Y5'). Assume no land is reclaimed for scenario testing.

(229) Normal Yearly Precipitation Height= 2.25 Units: m/Year Volume input of water over a year on an area of land = 2.4m on a point piece of land. If that fell on a m² of land, the total volume would be in m³. Data from Wikipedia. 2.3431

(230) Normal Yearly Precipitation Input= Normal Yearly Precipitation Height*(1-Normal ET Fraction)*Precipitation Collection Efficiency *CF Volume to Area Units: m³/(Year*Hectare)

(231) Normalized Catchment Area Equivalent= ((Infrastructure Production Capacity/Normal Yearly Precipitation Input)-Johore Initial Catchment Area Hectares)/Total Land Area Units: dmnl

(232) Normalized Desired Current Price Increase= Desired Domestic Price due to Current Revenue Shortfall/Domestic Unit Base Price *Unit Year Units: 1

(233) Normalized Desired Future Price Increase=

- Desired Increase in Domestic Price due to Projected Revenue Shortfall/Domestic Unit Base Price
 *Unit Year Units: 1
- (234) Normalized Economic Intensity of Water= Total Cost of Water to Economy/Actual GDP Units: dmnl
- (235) Normalized Economic Pressure to Reduce Water Price= Economic Pressure to Reduce Economic Intensity of Water/Normal Economic Pressure on Water Price Reduction Units: 1
- (236) Normalized GDP Productivity= Actual GDP/Economic Productivity Units: 1
- (237) Normalized Household Intensity= Actual Domestic Use/Desired Maximum Household Water Intensity Units: dmnl
- (238) Normalized Overshoot of Domestic Use= Overshoot of Actual to Desired Average Domestic Use/Desired Maximum Household Water Intensity Units: 1
- (239) Normalized Projected Domestic Demand Overshoot= Overshoot of Projected Domestic Demand/Maximum Desired Domestic Demand Units: 1
- (240) Number of Households= Population/Average Household Size Units: Household
- (241) Number of Jobs= Actual GDP*Labor Intensity of Production Units: Person
- (242) Outflow from Domestic Demand= Actual Reduction/Time to Reduce Household Water Intensity Units: m3/(Year*Year*Household) Outflow from Domestic Demand represents the negative change in Average Household Water Intensity per unit time.
- (243) Outflow from PUB Capital= MAX(0,Relative Capital Availability*Total Cost of Water to Utility) Units: Dollar/Year
- (244) Outflow to Economic Water Intensity= Actual Reduction in Economic Intensity Units: m3/(Dollar*Year)
- (245) Outflow to Population= Net Outflow to Population Units: Person/Year
- (246) Overshoot of Actual to Desired Average Domestic Use= MAX(0,(Perceived Actual Domestic Use-Desired Maximum Household Water Intensity)) Units: m3/(Year*Household)
- (247) Overshoot of Projected Domestic Demand= MAX(0, (Projected Domestic Demand-Maximum Desired Domestic Demand)) Units: m3/Year
- (248) Perceived Actual Domestic Use= Perceived Domestic Demand/Number of Households Units: m3/(Year*Household)
- (249) Perceived Domestic Demand= SMOOTH(Total Domestic Demand, TimeToPerceive Domestic Demand) Units: m3/Year This is the perceived socioeconomic demand.
- (250) Perceived Water Demand of Economy= SMOOTH(Total Economic Water Demand, TimeToPerceive Water Demand of Economy) Units: m3/Year This is the perceived socioeconomic demand.
- (251) PerceivedCost per Unit Infrastructure= SMOOTH(Unit Cost of Infrastructure, TimeToPerceive Infrastructure Unit Costs) Units: Dollar/m3 This is the perceived socioeconomic demand.
- (252) PerceivedFractional Appreciation Rate= SMOOTH(Normal Fractional Appreciation, TimeToPerceive PUB Capital) Units: dmnl/Year This is the perceived socioeconomic demand.
- (253) PerceivedPUB Capital= SMOOTH(PUB Capital, TimeToPerceive PUB Capital) Units: Dollar This is the perceived socioeconomic demand.

(254) Planning Period= 20 Units: Year GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'BK5'). Assume planning period to be about 15 years.

(255) Policy Protected Land= 7000 Units: Hectare This ia a policy variable representing land policy protected water resources and other natural resources by setting aside land that cannot be developed.

(256) Population= INTEG (Inflow to Population- Outflow to Population, 5.1*10^6) Units: Person Population initialized at 1.6E6 in the year 1960. Rose to 5.1E6 by 2010 and is expected to grow to 6-8E6 by 2060.

(257) Precipitation Collection Efficiency= 1 Units: dmnl It is unrealistic to assume that all the precipitation that falls is collectable, evapotranspiration aside. However, start with 1. This variable accounts for that.

(258) Precipitation Input= (1+STEP(Precipitation Step Height,Precipitation Step Time)+STEP(1,Precipitation Noise Start Time)*RANDOM NORMAL(-4 , 4 , 0 , Precipitation Noise Standard Deviation , Precipitation Noise Seed))*Normal Yearly Precipitation Height Units: m/Year The test input can be configured to generate a step, pulse, linear ramp, exponential growth, sine wave, and random variation. The initial value of the input is 1 and each test input begins at a particular start time. The magnitudes are expressed as fractions of the initial value.

(259) Precipitation Noise Seed= 100 Units: dmnl Varying the random number seed changes the sequence of realizations for the random variable.

(260) Precipitation Noise Standard Deviation= 0.1 Units: dmnl The standard deviation in the random

noise. The random fluctuation is drawn from a normal distribution with min and max values of +/- 4. The user can also specify the random number seed to replicate simulations. To generate a different random number sequence, change the random number seed. The standard deviation range for the precipitation input signal historically has a maximum range of 0.25 m/year and 1 m/year. With an average input of 2.25m/year, this translates into approximately a 0.1-0.5 fractional deviation and these are the two inputs used for the high and low amplitude precipitation signal.

(261) Precipitation Noise Start Time= 0 Units: Year The time at which the random noise in the input begins.

(262) Precipitation Step Height= 0 Units: dmnl The height of the step increase in the input.

(263) Precipitation Step Time= 0 Units: Year The time at which the step increase in the input occurs.

(264) Pressure to Decrease Price= MIN(1, (Elasticity of Pressure to Reduce Price to Domestic Affordability(Ratio of Actual to Acceptable Cost)+Elasticity of Pressure to Reduce Price to Economic Pressure (Normalized Economic Pressure to Reduce Water Price))) Units: 1

(265) Pressure to Increase Price= MAX(Elasticity of Pressure to Current Shortfall(Normalized Desired Current Price Increase), Elasticity of Pressure to Future Shortfall(Normalized Desired Future Price Increase)) Units: 1

(266) Production Capacity of Initial Installed Catchment= Total Installed Catchment Area*Normal Yearly Precipitation Input Units: m3/Year The production capacity of the initial installed catchment area is given by the installed catchment area at time t = 0, multiplied by the

precipitation point flux over the surface. Losses to precipitation and collection are adjusted through the precipitation input.

(267) Projected Costs per Unit Infrastructure= PerceivedCost per Unit Infrastructure *(1 + FractionalTrend in IUC *(TimeToPerceive Infrastructure Unit Costs + ForecastHorizon for Projecting PUB Capital)) Units: Dollar/m³

(268) Projected Desired Capital Inflow= Projected Desired Capital Stock/Minimum Capital Residence Time Units: Dollar/Year

(269) Projected Desired Capital Stock= Desired Capital Buffer*(Projected Total Cost of Infrastructure)+Cost of Proposed Expansion Units: Dollar Desired stock of water resources.

(270) Projected Domestic Demand= MAX(0, Perceived Domestic Demand *(1 + FractionalTrend in Domestic Demand *(TimeToPerceive Domestic Demand + ForecastHorizon for Projecting Demand))) Units: m³/Year

(271) Projected Economic Demand= MAX(0, Perceived Water Demand of Economy *(1 + FractionalTrend in Economic Demand *(TimeToPerceive Water Demand of Economy + ForecastHorizon for Projecting Demand))) Units: m³/Year

(272) Projected Fractional Appreciation= PerceivedFractional Appreciation Rate *(1 + FractionalTrend in Fractional Appreciation *(TimeToPerceive PUB Capital +ForecastHorizon for Projecting PUB Capital)) Units: dmnl/Year

(273) Projected Infrastructure= Infrastructure Production Capacity+Infrastructure Under Construction Units: m³/Year

(274) Projected PUB Capital= PerceivedPUB Capital *(1 + FractionalTrend in PUB Capital *(TimeToPerceive PUB Capital + ForecastHorizon

for Projecting PUB Capital)) Units: Dollar

(275) Projected Revenue= Domestic Unit Base Price*Projected Domestic Demand+Nondomestic Unit Price *Projected Economic Demand+Projected Fractional Appreciation*Projected PUB Capital Units: Dollar/Year

(276) Projected Shortfall in Revenue= MAX(0, Projected Desired Capital Inflow-Projected Revenue) Units: Dollar/Year

(277) Projected Total Cost of Infrastructure= Projected Costs per Unit Infrastructure*Projected Infrastructure Units: Dollar/Year

(278) Projected Water Resources= (Infrastructure in Planning+Infrastructure Production Capacity+Infrastructure Under Construction -Change in Infrastructure Production Capacity due to Juhore)*Natural Residence Time Units: m³

(279) Proposed Catchment Area Expansion= Desired Increase in Future Water Supply Units: m³/Year Proposed Infrastructure Expansion is equal to the Desired increase in future water supply adjusted for infrastructure in the construction and planning phases.

(280) Proximity of Average Domestic Consumption to the Floor= Floor to Household Consumption/Actual Domestic Use Units: 1 [0,2] As the Floor to household consumption goes up, the proximity of consumption to that floor goes up. Assume that consumption cannot go below the floor. As Actual domestic use goes up, the proximity goes down. When actual use is equal to the floor, then the proximity will be one.

(281) PUB Capital= INTEG (Inflow to PUB Capital-Outflow from PUB Capital, 3*10⁹) Units: Dollar Initialize PUB Capital at the amount of money PUB had in 1960. It was initialized to

1.77093×10^8 in 1960 for the equilibrium model, but might have been less or more. In 2010 the model showed PUB Capital as 3 billion.

(282) Ramp Switch= 1 Units: dmnl Switches the ramp for cost on and off

(283) Rate of Removal of Land from Land Available for Storage= MIN(Desired Urbanization Rate,Maximum Inflow to Urbanized Land) Units: Hectare/Year

(284) Ratio of Actual to Acceptable Cost= MAX(0, Actual Cost of Water to Households/Acceptable Cost of Water to Households) Units: 1 When the Actual Cost of Water to Households goes up, the shortfall would go up beyond what it would be otherwise. If the Acceptable cost goes up, the Shortfall should go down.

(285) Ratio of Demand for Land for Urbanization vs Storage= IF THEN ELSE (Desired Increase in Urbanized Land+Desired Increase in Storage Volume Area =0, 0, Desired Increase in Urbanized Land/(Desired Increase in Storage Volume Area +Desired Increase in Urbanized Land)) Units: 1

(286) Ratio of Nondomestic to Domestic Unit Price= 1 Units: dmnl In general, the ratio of domestic to nondomestic base price has been two, but with the new water policy it is one.

(287) Reclamation Rate= Normal Reclamation Rate*Total Land Area Units: Hectare/Year

(288) Reference Temperature= 30 Units: C The reference temperature is the average yearly temperature for Singapore. How temperature might play out for temperate climates should be carefully considered in adapting this model to other cities with more variable climates than that of Singapore's.

(289) Relative Capital Availability= Elasticity of Capital Outflow to Availability(Maximum Outflow

to PUB Capital /Total Cost of Water to Utility)
Units: dmnl

(290) Relative Water Availability= Elasticity of Water Consumption to Availability(Maximum Outflow to Water Resources /Total Socioeconomic Demand) Units: dmnl Relative Water Availability is the ratio of total supply to demand. Supply above or equal to supply generates a relative water availability of one.

(291) Return on Education= 1.114 Units: dmnl Human Capital-Augmenting factor as a function of average years of education of population. Equation based on Hall1999, p89. GET XLS DATA('datainput-04122011.xls', 'Sheet1', 'A', 'O5'). In 2010 it was 1.114; there is some evidence it has been growing but assume that it is constant for scenario runs.

(292) Revenue from Domestic= Domestic Unit Price*Total Domestic Sales*Domestic Collection Efficiency Units: Dollar/Year

(293) Revenue from Nondomestic= Nondomestic Unit Price*Total Nondomestic Sales*Nondomestic Collection Efficiency Units: Dollar/Year

(294) SAVEPER = TIME STEP Units: Year [0,?] The frequency with which output is stored.

(295) Shortfall in Future Supply= MAX(0, Desired Water Coverage*Total Projected Socioeconomic Demand-Projected Water Resources) Units: m3 Shortfall in future supply is the projected socioeconomic demand multiplied by the duration over which planners would like to be covered (a buffer) minus current water resources.

(296) Shortfall in Storage Volume= MAX(0, Desired Storage Volume-Storage Volume of Infrastructure) Units: m3

(297) Sine Amplitude= 1 Units: dmnl The ampli-

tude of the sine wave in the input. Assume the amplitude of the temperature sine amplitude is 2C.

(298) Sine Period= 20 Units: Year The period of the sine wave in the input.

(299) Sine Start Time= 0 Units: Year The time at which the sine wave fluctuation in the input begins.

(300) Singapore Initial Catchment Area Hectares= 1000 Units: Hectare Assume that the initial installed catchment area in Singapore in 1960 is less than half of the island area.

(301) Step Switch= 0 Units: dmnl This switches the step for cost on and off

(302) Storage Volume Area= INTEG (Inflow to Storage Area, 14000) Units: Hectare See Storage Volume of infrastructure documentation for information on initial value. 520.5. In 2010 there were 14000 hectares of water storage.

(303) Storage Volume of Infrastructure= Average Storage Volume per Unit Storage Area*Storage Volume Area Units: m³

(304) Switch for Johore Catchment Area= 1 Units: dmnl This switch is created for the Johore Catchment Area. When it is switched off, then it will impact the Average Infrastructure Cost Increase and the Infrastructure Production Capacity.

(305) Temp Switch= 1 Units: dmnl Temp switch turns the temp adjustment on and off.

(306) Temperature Adjustment= (RAMP(Temperature Ramp Slope, Temperature Ramp Start Time, Temperature Ramp End Time)+STEP(1,Sine Start Time)*Sine Amplitude*SIN(2*3.14159/Sine Period*Time))*CF Celsius Units: C The test input can be configured to generate a step, pulse, linear ramp, exponential growth, sine wave, and random variation. The initial value of the input is 1 and each test input begins at a particular start time.

The magnitudes are expressed as fractions of the initial value. The temperature input is an input that adjusts the average yearly temperature.

(307) Temperature Input= Reference Temperature+Temperature Adjustment*Temp Switch Units: C Temperature input is the Reference Temperature Adjusted for the Temperature Signal for climate change scenarios.

(308) Temperature Ramp End Time= 100 Units: Year The end time for the ramp input. Temperature is assumed to rise gradually (linearly) over the 100 year simulation).

(309) Temperature Ramp Slope= 0.025 Units: 1/Year The slope of the linear ramp in the input. Assume that the slope is 0.025C/Year, or, over 100 years, 2.5C change in temp, which is in line with climate change scenarios.

(310) Temperature Ramp Start Time= 0 Units: Year The time at which the ramp in the input begins.

(311) Threshold Proximity= 0.35 Units: dmnl

(312) TIME STEP = 0.25 Units: Year [0,?] The time step for the simulation.

(313) Time to Adjust Water Intensity of Economy= 5 Units: Year The time to adjust the water intensity of the economy takes much longer than for households due to the scale of operations and inflexibility of economic activity to changing water technologies.

(314) Time to Change Mental Model about Household Water Cost= 5 Units: Years Assume that people don't like to pay much more for things than they did 5-10 years ago.

(315) Time to Grow Household Water Intensity= 10 Units: Year This is the time it takes for the capacity in domestic water intensity growth to be

taken up by an increase in household services. It reflects the amount of time it takes households to increase services and household appliances that use water until the extra household budget for water reaches zero.

(316) Time to Increase Infrastructure in Planning= 10 Units: Year GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'BJ5')

(317) Time to Order Maintenance= 1 Units: Year

(318) Time to Reduce Household Water Intensity= 1 Units: Year Let's assume that households can adjust water intensity within a year.

(319) TimeToPerceive Domestic Demand= 2.5 Units: Year

(320) TimeToPerceive Infrastructure Unit Costs= 3 Units: Year

(321) TimeToPerceive PUB Capital = 1 Units: Year

(322) TimeToPerceive Water Demand of Economy= 2.5 Units: Year

(323) Total Actual Domestic Use= Relative Water Availability*Total Domestic Demand Units: m3/Year

(324) Total Actual Economic Use= Relative Water Availability*Total Economic Water Demand Units: m3/Year

(325) Total Cost of Water to Economy= Total Actual Economic Use*Nondomestic Unit Price Units: Dollar/Year

(326) Total Cost of Water to Utility= Cost of Operation+Maintenance Cost of Production+ Cost of Current Expansion +Depreciation of PUB Capital Units: Dollar/Year

(327) Total Domestic Demand= Number of Households*Average Household Water Intensity Units: m3/Year

(328) Total Domestic Sales= (1-Unaccounted for Water)*Total Actual Domestic Use Units: m3/Year

(329) Total Economic Water Demand= Economic Productivity*Average Water Intensity of Economy Units: m3/Year

(330) Total Installed Catchment Area= Installed Catchment Area in Singapore+Johore Initial Catchment Area Hectares *(1-STEP(1, 50)) Units: Hectare

(331) Total Land Area= Undeveloped Land+Urbanized Land+Storage Volume Area Units: Hectare

(332) Total Nondomestic Sales= Total Actual Economic Use*(1-Unaccounted for Water) Units: m3/Year

(333) Total Projected Socioeconomic Demand= Projected Domestic Demand+Projected Economic Demand Units: m3/Year

(334) Total Revenue= Revenue from Domestic+Revenue from Nondomestic Units: Dollars/Year

(335) Total Socioeconomic Demand= (Total Domestic Demand+Total Economic Water Demand)*(1+Unaccounted for Water) Units: m3/Year

(336) Trickledown Effect of GDP= 0.9 Units: dmnl Trickledown Effect of GDP is the ratio of GNI to GDP, assuming all the income goes into the pockets of the population. It is initialized at 0.9 for scenario testing. There is some evidence that it has been decreasing over time, but assume constant for the scenarios. GET XLS DATA('datainput-04122011.xls' , 'Sheet1' , 'A' , 'BA5')

(337) Unaccounted for Water= 0.05 Units: dmnl GET XLS DATA('datainput-04122011.xls' ,

'Sheet1' , 'A' , 'BL5') This variable represents the fact that not all water that is produced and distributed is accounted for. Changes over time. By 2010, reported to be 5% of water unaccounted for; a normal number is 25%. For the scenario testing, Unaccounted for Water is set to the value at t=2010; here it is 5% of water is unaccounted for. 0.05

(338) Undeveloped Land= INTEG (Reclamation Rate-Inflow to Storage Area-Rate of Removal of Land from Land Available for Storage , Initial Total Land Area-(Urbanized Land + Storage Volume Area)) Units: Hectare Initial Total Land Area-Urbanized Land-Storage Volume Area. In 2010, the undeveloped land is around 3830 Hectares.

(339) Unit Cost of Infrastructure= (Cost of Operation+Maintenance Cost of Production)/Infrastructure Production Capacity Units: Dollar/m³

(340) Unit Cost of Infrastructure Expansion= Normal Financial Intensity of Infrastructure Expansion*Elasticity of Infrastructure Expansion Financial Intensity to Normalized Catchment Area (Normalized Catchment Area Equivalent)*Average Infrastructure Cost Increase Units: Year*Dollar/m³ Unit cost of infrastructure (Cost per unit infrastructure has units Dollars/m³/year). This variable has been adjusted from the historical data to include an estimation of cost changes.

(341) Unit Year= 1 Units: Year This variable is used to adjust flow rates, such that if a policy is set for a maximum of some variable (like population), when determining the maximum inflow rate a new time constant is not required. Equations that

use Unit Year assume that the adjustment is made within a year.

(342) Unitless Economic Capital= CF Economic Capital*Economic Capital Units: 1

(343) Urbanized Land= INTEG (Rate of Removal of Land from Land Available for Storage, 65000) Units: Hectare Urbanized Area is considered to be any built up area that is not agricultural or protected. In 2010, there were 65000 hectares of urbanized land. Initial Percent Land Area Urbanized*Initial Total Land Area

(344) Water Consumption Rate= Relative Water Availability*Total Socioeconomic Demand Units: m³/Year

(345) Water Production= Affordability of Operation*MAX(0, Actual Production Capacity of Infrastructure) Units: m³/Year

(346) Water Resources= INTEG (Inflow to Water Resources-Natural Discharge-Water Consumption Rate, Total Socioeconomic Demand*Minimum Residence Time+Storage Volume of Infrastructure) Units: m³ Assume that the stock of water resources is the amount of water that people have access to at any one time. When set to equilibrium, it was set to (Infrastructure Production Capacity-Total Socioeconomic Demand)*Minimum Residence Time

(347) Water Tariff= Base Water Tariff*Elasticity of Water Tariff to Domestic Intensity(Normalized Household Intensity) Units: Dollar/m³

(348) Workforce= Desired Fraction Population Working*Population Units: Person Workers, body count. Derived from data published in the Penn World Tables, version 6.3. (L)

Bibliography

- [1] R. de Koninck, J. Drolet, and M. Girard, *Singapore: an atlas of perpetual territorial transformation*. Singapore: National University of Singapore Press, 2008.
- [2] PUB, “PUB Annual Report,” Singapore, 1965.
- [3] PUB, “PUB Annual Report,” Singapore, 1975.
- [4] PUB, “PUB Annual Report,” Singapore, 1985.
- [5] PUB, “PUB Annual Report,” Singapore, 1990.
- [6] PUB, “PUB Annual Report,” Singapore, 1995.
- [7] PUB, “PUB Annual Report,” Singapore, 2000.
- [8] PUB, “PUB Annual Report,” Singapore, 2010.
- [9] F. Krausmann, M. Fischer-Kowalski, H. Schandl, and N. Eisenmenger, “The Global Sociometabolic Transition,” *Journal of Industrial Ecology*, vol. 12, no. 5/6, pp. 637–656, 2008.
- [10] N. B. Schulz, “The Direct Material Inputs into Singapore’s Development,” *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 117–131, 2007.
- [11] R. T. Corlett, “The Ecological Transformation of Singapore,” *Journal of Biogeography*, vol. 19, no. 4, pp. 411–420, 1992.
- [12] M. Fischer-Kowalski and C. Amann, “Beyond IPAT and Kuznets Curves: Globalization as a Vital Factor in Analysing the Environmental Impact of Socio-Economic Metabolism,” *Population & Environment*, vol. 23, pp. 7–47, 2001.

- [13] M. Chertow, “The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact,” *Journal of Industrial Ecology*, vol. 4, no. 4, pp. 13–29, 2000.
- [14] P. Lamberson, “Causal Loop Diagram describing the potential “Tech Nightmare” of society’s progress.” Personal communication, June 2010. This diagram was also shown in one of the last lectures in the second half of System Dynamics, 15.872, Spring 2010.
- [15] G. M. Turner, “A Comparison of the Limits to Growth with 30 Years of Reality,” *Global Environmental Change*, vol. 18, no. 3, pp. 397–411, 2008.
- [16] S. P. Simonović, “Assessment of water resources through system dynamics simulation: from global issues to regional solutions,” in *Proceedings of the 36th Annual Hawaii International Conference on System Sciences, 2003*, p. 9, 2003.
- [17] X. Bai, “Integrating Global Environmental Concerns into Urban Management: The Scale and Readiness Arguments,” *Journal of Industrial Ecology*, vol. 11, no. 2, 2007.
- [18] C. Aichinger, *Institutional Structures for Water Management in the Eastern United States*, chapter 10, pp. 217–234. The Water Environment of Cities, Springer Science and Business Media, LLC, 2009.
- [19] A. Milman and A. Short, “Incorporating resilience into sustainability indicators: An example for the urban water sector,” *Global Environmental Change*, vol. 18, no. 4, pp. 758–767, 2008.
- [20] Y. S. Tan, T. J. Lee, and K. Tan, *Clean, Green and Blue : Singapore’s Journey towards Environmental and Water Sustainability*. Singapore: Institute of Southeast Asian Studies, illustrated ed., 2009.
- [21] J. Sterman, *Business dynamics : systems thinking and modeling for a complex world*. Boston: McGraw-Hill College, 2006.
- [22] M. Fischer-Kowalski, “Society’s Metabolism: The Intellectual History of Materials Flow Analysis, Part I, 1860-1070,” *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 61–78, 1998.

- [23] M. Fischer-Kowalski and W. Hottler, “Society’s metabolism: The intellectual history of materials flow analysis, part II, 1970–1998,” *Journal of Industrial Ecology*, vol. 2, no. 4, pp. 107–136, 1999.
- [24] F. Krausmann, S. Gingrich, N. Eisenmenger, K. H. Erb, H. Haberl, and M. Fischer-Kowalski, “Growth in global materials use, GDP and population during the 20th century,” *Ecological Economics*, 2009.
- [25] J. McNeill, *Something new under the sun: an environmental history of the twentieth-century world*. New York: W.W. Norton & Company, 2000.
- [26] A. Behrens, S. Giljum, J. Kovanda, and S. Niza, “The material basis of the global economy: Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies,” *Ecological Economics*, vol. 64, pp. 444–453, 12 2007.
- [27] P. M. Vitousek, H. A. Mooney, J. Lubchenco, and J. M. Melillo, “Human domination of Earth’s ecosystems,” *Science*, vol. 277, no. 5325, p. 494, 1997.
- [28] J. Merkel and L. H. Litten, “The sustainability challenge,” *New Directions for Institutional Research*, vol. 2007, no. 134, pp. 7–26, 2007.
- [29] U. N. W. C. on Environment and Development, *Our Common Future*. Oxford University Press, 1987.
- [30] J. Liu, T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor, “Complexity of Coupled Human and Natural Systems,” *Science*, vol. 317, pp. 1513–1516, September 2007.
- [31] T. W. Fitzhugh and B. D. Richter, “Quenching urban thirst: growing cities and their impacts on freshwater ecosystems,” *BioScience*, vol. 54, no. 8, pp. 741–754, 2004.
- [32] L. A. Baker, *The water environment of cities*. New York: Springer, illustrated ed., 2009.
- [33] J. Lundqvist, C. Tortajada, O. Varis, and A. Biswas, “Water management in megacities,” *Ambio*, vol. 34, pp. 267–8, 5 2005.

- [34] J. S. Baron, N. L. Poff, P. L. Angermeier, C. N. Dahm, P. H. Gleick, N. G. Hairston Jr., R. B. Jackson, C. A. Johnston, B. D. Richter, and A. D. Steinman, “Meeting Ecological and Societal Needs for Freshwater,” *Ecological Applications*, vol. 12, no. 5, pp. 1247–1260, 2002.
- [35] C. Tortajada, “Water Management in Singapore,” *Water Resources Management*, vol. 22, no. 2, pp. 227–240, 2006.
- [36] T.-C. Wong and L.-H. A. Yap, *Four decades of transformation: land use in Singapore, 1960-2000*. Eastern Universities Press, 2004.
- [37] A. Ford, *Modeling the environment*. Island Pr, 2009.
- [38] I. Winz, G. Brierly, and S. Trowsdale, “The Use of System Dynamics Simulation in Water Resources Management,” *Water Resources Management*, vol. 23, pp. 1301–1323, 2009.
- [39] B. Güneralp and K. C. Seto, “Environmental impacts of urban growth from an integrated dynamic perspective: A case study of Shenzhen, South China,” *Global Environmental Change*, 2008.
- [40] PUB, “Water Department: An Introduction,” Singapore, 1982. Singapore library call number: R Sing q354.595700 871 SIN.
- [41] P. Slovic, “Going Beyond the Red Book: The Sociopolitics of Risk,” *Human and Ecological Risk Assessment*, vol. 9, no. 5, pp. 1181–1190, 2003.
- [42] A. E. Farrell, J. Jäger, and S. D. VanDeveer, *Understanding Design Choices*, ch. 1, pp. 1–24. Assessments of regional and global environmental risks: designing processes for the effective use of science in decisionmaking, Washington, D.C.: Resources for the Future, 2006.
- [43] F. Brand, “Critical natural capital revisited: ecological resilience and sustainable development,” *Ecological Economics*, pp. 605–612, 2009.

- [44] A. C. McIntosh and C. E. Yñiguez, *Second Water Utilities Data Book: Asian and Pacific Region*. Manila, Philippines: Asian Development Bank, October 1997.
- [45] J. Lubchenco, “Entering the century of the environment: a new social contract for science,” *Science*, vol. 279, no. 5350, p. 491, 1998.
- [46] C. S. Holling, “Understanding the Complexity of Economic, Ecological, and Social Systems,” *Ecosystems*, vol. 4, pp. 390–405, 2001.
- [47] J. J. Kay, H. A. Regier, M. Boyle, and G. Francis, “An ecosystem approach for sustainability: addressing the challenge of complexity,” *Futures*, vol. 31, no. 7, pp. 721 – 742, 1999.
- [48] S. T. A. Pickett, M. L. Cadenasso, J. M. Grove, C. H. Nilon, R. V. Pouyat, W. C. Zipperer, and R. Costanza, “URBAN ECOLOGICAL SYSTEMS: Linking Terrestrial Ecological, Physical, and Socioeconomic Components of Metropolitan Areas,” *Annual Review of Ecology and Systematics*, vol. 32, no. 1, pp. 127–157, 2001.
- [49] L. M. A. Bettencourt, J. Lobo, D. Helbing, C. Kühnert, and G. B. West, “Growth, innovation, scaling, and the pace of life in cities.,” *Proc Natl Acad Sci U S A*, vol. 104, pp. 7301–6, 4 2007.
- [50] M. Batty, “The size, scale, and shape of cities.,” *Science*, vol. 319, pp. 769–71, 2 2008.
- [51] C. Kennedy, J. Cuddihy, and J. Engel-Yan, “The changing metabolism of cities,” *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 43–59, 2007.
- [52] E. D. E. Decker, S. Elliott, F. Smith, D. Blake, and S. Rowland, “Energy and material flow through the urban ecosystem,” *Annual Review of Energy and the Environment*, vol. 25, pp. 685–740, 2000.
- [53] A. Wolman, “The Metabolism of Cities,” *Scientific American*, vol. 213, no. 3, pp. 179–190, 1965.
- [54] A. de Sherbinin, D. Carr, S. Cassels, and L. Jiang, “Population and Environment,” *Annual Review Environment and Resources*, vol. 32, pp. 345–373, 2007.

- [55] W. E. Rees, “Revisiting Carrying Capacity: Area-Based Indicators of Sustainability,” *Population and Environment*, vol. 17, no. 3, pp. 195–215, 1996.
- [56] P. Waggoner and J. Ausubel, “A framework for sustainability science: A renovated IPAT identity,” *Proceedings of the National Academy of Sciences*, vol. 99, no. 12, pp. 7860–7865, 2002.
- [57] S. Bringezu, “Industrial ecology and material flow analysis,” *Perspectives on industrial ecology*, 2003.
- [58] P. L. Daniels and S. Moore, “Approaches for Quantifying the Metabolism of Physical Economies: Part I: Methodological Overview,” *Journal of Industrial Ecology*, vol. 5, no. 4, pp. 69–93, 2001.
- [59] P. L. Daniels, “Approaches for Quantifying the metabolism of Physical Economies: A Comparative Survey: Part II: Review of Individual Approaches,” *Journal of Industrial Ecology*, vol. 6, no. 1, pp. 65–88, 2002.
- [60] M. Wackernagel, “Methodological advancements in footprint analysis,” *Ecological Economics*, 2009.
- [61] W. Gerbens-Leenes, A. Y. Hoekstra, and T. H. Van der Meer, “The water footprint of bioenergy,” *Proceedings of the National Academy of Sciences*, vol. 106, no. 25, p. 10219, 2009.
- [62] M. Falkenmark and J. Rockström, “The new blue and green water paradigm: Breaking new ground for water resources planning and management,” *Journal of Water Resources Planning and Management*, vol. 132, p. 129, 2006.
- [63] A. Y. Hoekstra, “Human appropriation of natural capital: A comparison of ecological footprint and water footprint analysis,” *Ecological Economics*, vol. 68, pp. 1963–1974, 5 2009.
- [64] C. J. Vörösmarty, E. M. Douglas, P. A. Green, and C. Revenga, “Geospatial indicators of emerging water stress: an application to Africa,” *Ambio*, vol. 34, pp. 230–6, 5 2005.

- [65] Eurostat, *Economy-wide material flow accounts and derived indicators: a methodological guide*. Luxembourg: Office for Official Publications of the European Communities, 2001.
- [66] D. E. Bloom, D. Canning, and G. Fink, “Urbanization and the Wealth of Nations,” *Science*, vol. 319, no. 5864, p. 772, 2008.
- [67] P. H. Gleick, “The human right to water,” *Water Policy*, vol. 1, pp. 487–503, 1998.
- [68] S. Abdallah, S. Thompson, J. Michaelson, N. Marks, and N. Steuer, “The Happy Planet Index 2.0: Why good lives don’t have to cost the Earth,” *New Economics Foundation*, 2009.
- [69] Y. K. Ng, “Environmentally responsible happy nation index: Towards an internationally acceptable national success indicator,” *Social Indicators Research*, vol. 85, no. 3, pp. 425–446, 2008.
- [70] R. York, E. A. Rosa, and T. Dietz, “STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts,” *Ecological Economics*, vol. 26, pp. 351–365, 2003.
- [71] S. P. Simonović, “World water dynamics: global modeling of water resources,” *Journal of Environmental Management*, vol. 66, no. 3, pp. 249–267, 2002.
- [72] K. A. Stave, “A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada,” *Journal of Environmental Management*, vol. 67, no. 4, pp. 303–313, 2003.
- [73] K. Madani and M. A. Mariño, “System dynamics analysis for managing Iran’s Zayandeh-Rud river basin,” *Water Resources Management*, vol. 23, no. 11, pp. 2163–2187, 2009.
- [74] W. Rees and M. Wackernagel, “Urban ecological footprints: why cities cannot be sustainable: and why they are a key to sustainability,” *Urban Ecology*, pp. 537–555, 2008.
- [75] E. A. Rosa, R. York, and T. Dietz, “Tracking the anthropogenic drivers of ecological impacts,” *Ambio*, vol. 33, pp. 509–12, 12 2004.

- [76] N. B. Grimm, S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs, “Global change and the ecology of cities.,” *Science*, vol. 319, pp. 756–60, 2 2008.
- [77] S. Barles, “Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues,” *Journal of Environmental Planning and Management*, vol. 53, no. 4, pp. 439–455, 2010.
- [78] F. Krausmann, “Land use and industrial modernization: an empirical analysis of human influence on the functioning of ecosystems in Austria 1830-1995,” *Land Use Policy*, vol. 18, pp. 17–26, 2001.
- [79] J. E. Fernández, “Resource Consumption of New Urban Construction in China,” *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 99–115, 2007.
- [80] X. Bai, “Industrial ecology and the global impacts of cities,” *Journal of Industrial Ecology*, vol. 11, no. 2, pp. 1–6, 2007.
- [81] A. N. Saldivar-Sali, “A global typology of cities: classification tree analysis of urban resource consumption,” master’s thesis, Massachusetts Institute of Technology, Building Technology Program, Department of Architecture, 2010.
- [82] B. Turner, R. E. Kasperson, P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, J. X. Kasperson, A. Luers, M. L. Martello, C. Polisy, A. Pulsipher, and A. Schiller, “A framework for vulnerability analysis in sustainability science,” *Proceedings of the National Academy of Science*, vol. 100, no. 14, pp. 8074–8079, 2003.
- [83] Y. Barlas, *System dynamics: systemic feedback modeling for policy analysis*, ch. 5.12, pp. 1131–1175. Knowledge for Sustainable Development - An Insight into the Encyclopedia of Life Support, Paris, France and Oxford, U.K.: UNESCO Publishing, Eolss Publishers, 2002.
- [84] I. Whyte, *World Without End? Environmental Disaster and the Collapse of Empires*. I.B.Tauris, 2008.
- [85] G. Hardin, “The Tragedy of the Commons,” *Science*, vol. 162, no. 3859, pp. 1243–1248, 1968.

- [86] R. G. Dudley, “A basis for understanding fishery management dynamics,” *System Dynamics Review*, vol. 24, no. 1, 2008.
- [87] J. Layzer, *Crisis in the New England Fisheries*, chapter 10, pp. 251–277. The Environmental Case, Washington, D.C.: CQ Press, 2006.
- [88] W. Tuinstra, L. Hordijk, and M. Amann, “Using computer models in international negotiations,” *Environment*, vol. 41, pp. 32–42, November 1999.
- [89] E. Moxnes, “Misperceptions of basic dynamics: the case of renewable resource management,” *System Dynamics Review*, vol. 20, no. 2, pp. 139–162, 2004.
- [90] N. Oreskes, K. Shrader-Frechette, and K. Belitz, “Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences.,” *Science*, vol. 263, pp. 641–646, 2 1994.
- [91] M. R. Montgomery, “The urban transformation of the developing world.,” *Science*, vol. 319, pp. 761–4, 2 2008.
- [92] A. Y. Hoekstra and A. K. Chapagain, “Water footprints of nations: water use by people as a function of their consumption pattern,” *Integrated Assessment of Water Resources and Global Change*, vol. 21, pp. 35–48, 2007.
- [93] M. T. Rock, “The Dewatering of Economic Growth,” *Journal of Industrial Ecology*, vol. 4, no. 1, pp. 57–73, 2000.
- [94] J. F. Bruneau and S. Renzetti, “Water Use Intensities and the Composition of Production in Canada,” *Journal of Water Resources Planning and Management*, vol. 136, p. 72, 2010.
- [95] R. E. Hall and C. I. Jones, “Why do some countries produce so much more output per worker than others?,” *The Quarterly Journal of Economics*, pp. 83–116, February 1999.
- [96] H. A. Loaiciga, J. B. Valdes, R. Vogel, J. Garvey, and H. Schwarz, “Global warming and the hydrologic cycle,” *Journal of Hydrology*, vol. 174, no. 1-2, pp. 83–127, 1996.

- [97] B. C. O'Neill and N. Nakicenovic, "Learning from global emissions scenarios," *Environmental Research Letters*, vol. 3, p. 045014, 2008.
- [98] S. P. Simonović, *Managing water resources: methods and tools for a systems approach*. United Nations Educational, 2009.