Urban Water Systems: Demand Management and Sustainable Development

by

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Abstract

This thesis is about urban water demand management and its relationship to planning in the context of sustainable development.

A theory of the development of economic systems as dissipative, self-organizing systems was used as the basis for understanding sustainability. The level of development attainable is related to the rate of degradation of available energy and inversely related to environmental uncertainty. This 'development by self-organization' is unsustainable, whether based on non-renewable or renewable resources. A second concept of development relates to solving the problem of achieving desirable social goals. This can be called 'development by design'. Development by design in the context of sustainability involves a contradiction between short-term and long-term goals which cannot in principle be solved. Real life resolutions generally favour the short-term goals. The heuristic of an adaptability / efficiency trade-off was found to be as useful for issues of 'development by design' as it is for 'development by self-organization.' Since neither type of development is expected to be sustainable, the importance of preserving the conditions for renewed development after crisis are highlighted.

Urban water demand management helps to meet social goals with respect to adequate water supply and protection of local natural aquatic environments. By easing a restraint on urban growth, demand management promotes economic development. This accelerates the trend towards unsustainability. However, water demand management helps to maintain environmental local conditions needed for post-crisis recovery. This general analysis was supplemented by the analysis of three specific urban water demand management problems:

(1) In a case study based on recent planning initiatives in the Regional Municipality of Waterloo, Ontario, it was found that demand management had not been as well

integrated with the planning for water supply and wastewater infrastructure as it might have been.

(2) A simulation model was developed which forecasts water use, water prices and the timing of expansions in water supply capacity. The unique feature of the model is the incorporation of anticipatory price smoothing. The model was successful in illustrating the need for integrating price forecasting with demand forecasting and capacity expansion planning.

(3) There is the possibility with a summer water use price structure that customers with high summer water use may deliberately waste water in the winter. An analysis of summer water use pricing was done which determined the relationship of the price ratio (summer use price to base use price) to other pricing parameters needed to avoid such wastage.

An emphasis on water demand management, whether motivated by water availability limits, wastewater assimilation limits, or economic limits, is a symptom of the drive for efficiency. A need for more integrated planning is likely to be felt in systems which are approaching limits because of the increase in connectedness which occurs in such systems. Other issues raised were: the energy cost of water as an economic commodity, especially in times when the dollar cost of energy is increasing; the complexity of an urban water system in relation to its vulnerability to external (economic or natural) perturbation; long-term environmental carrying capacity; and the importance of avoiding measures which might reduce the variability, and hence the adaptability, of the city economy.

Acknowledgements

I would like to thank my supervisors, Professor James E. Robinson (Environment and Resource Studies) and Professor Barry L. Wills (Systems Design Engineering). From Jim Robinson, I learned most of what I knew about urban water systems before I started this work, and much of what I have learned during the process. Barry Wills provided a solid background for the modelling component of this work, encouraged exploration of new ideas that came up, and facilitated presentations and informal discussions on adaptability theory and hierarchy theory.

A couple of times the focus of research changed significantly because of comments or suggestions made. For these turning points, I must credit Professors Robbie Keith and Sally Lerner (Department of Environment and Resource Studies), who insisted on a more formal consideration of the 'environment' than I had originally intended, and Mario Giampietro (Istituto Nazionale della Nutrizione, Italy), who introduced me to adaptability theory.

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1
Introduction

The idea of sustainable development was brought to the attention of the world by the Brundtland Commission's report, 'Our Common Future' (World Commission on Environment and Development, 1987). Current economic development was recognized as often detrimental to future economic development, due to depletion of non-renewable resources and adverse effects on ecological processes, upon which economic systems depend. Sustainable development was defined there as "development without compromising the ability of future generations to meet their own needs." This definition addresses the issue of sustainability, but leaves open the question of what development is. Because of the connection with the natural environment, term *sustainable development* has been expanded to *ecologically sustainable economic development* (Verbruggen and Kuik, 1991). Since the publication of the Brundtland Commission's report in 1987, sustainable development rapidly became an important policy issue, both internationally and nationally. Jim MacNeill, who managed the UN's Brundtland Commission project, stated that "The response to 'Our Common Future' has been greater than anything one could have expected" (MacNeill, 1989). Referring to the Canadian situation, Mitchell and Shrubsole (1994) have said:

> *Virtually all governments identify sustainable development as the overriding framework within which water planning, management, and development should occur.*

The subject of this thesis is urban water demand management in the context of sustainable development. Managing demand for water, of course, affects water supply planning, but it also affects wastewater system planning. In practice the need to integrate demand management into planning for water supply, and for wastewater treatment is not always recognized, or if recognized, may not be adequately realized (Robinson et al., 1984). There are various demand management methods, which may involve the regulation of certain water uses, or the encouragement of change in social attitudes towards water use and change in the technological efficiency of water use. Appropriate water pricing is a mechanism for advancing both attitudinal and technological change as they relate to water use. In this thesis, a limited selection of urban water demand management issues are examined intensively, and attention is paid to how water demand management conforms to an overall goal of sustainable development.

Providing water to cities is a factor in enabling the economic development of cities, and it is this role of water as an urban commodity which is the focus of this thesis. The other main way water interacts with cities is with respect to storm water and its management, but this aspect is not considered here. Since water destined to become a commodity is taken from the environment, and most of it is returned there as wastewater, there are clearly some environmental changes. These changes result from changes in water quality, and from changes in the spatial and temporal distribution of water in the environment. Measures which reduce this water flow through the city have variously been referred to as water conservation, water use efficiency and water demand management. Reducing the amount of this flow may enable a city to continue to develop in a situation where it would otherwise face a water shortage. Even when there is no shortage of water, demand management measures may be undertaken when there is a resulting reduction in cost. There is also a reduction of the impact of a city on its natural environment. It seems that water demand management can contribute to economic development, and also make such development more sustainable.

However, it is argued here that the situation is more complicated. Sustainable development needs to be viewed from a complex systems perspective. This view emphasizes the importance of scale, i.e. spatial and temporal extent (Allen and Starr, 1982; Giampietro, 1994), and the spontaneous emergence of organization in systems which are open to material and energy flows (Wicken, 1986; Ulanowicz, 1986, 1997; Schneider and Kay, 1989; Schneider and Kay, 1994a and 1994b). Ecological systems and socio-economic systems are both considered complex systems in this sense.

Viewed from this perspective, the contribution of demand management to sustainable development becomes somewhat elusive. This is to a large extent because the sustainability of development itself appears elusive when viewed from this perspective. In addition to the elusiveness of sustainable development, however, an increase in efficiency of water use or of other resource use which results from water demand management must be evaluated carefully. This is because of two phenomena typical of complex systems.

The first is the trade-off between adaptability and efficiency (Conrad, 1983). Adaptability results from the maintenance of potential courses of action, or potential behaviours. From a human perspective, some such courses of action may be utilized infrequently, so that maintaining the potential to use them represents a cost which is hard to justify. From an ecological viewpoint as well, competition among ecosystem components tends to wear away infrequently used potentials.

The second complex systems phenomenon connected with efficiency is a generalized form of the Jevons' paradox. In the nineteenth century, Jevons (1865) concluded that greater efficiency in the use of coal would hasten the depletion of British coal reserves. The paradox in generalized form, as used by Giampietro (1997), could be stated as follows: an increase in subsystem efficiency tends to cause an increase in size of the subsystem in relation to other subsystems, resulting in growth of the whole system. If the generalized Jevons' paradox applies to an increase in urban water use efficiency, it would mean there would be greater use of some resource or some resources as a result of water use efficiency, although not necessarily greater use of water.

Nevertheless, it seems that urban water demand management can contribute to sustainability. It certainly represents a set of possible courses of action which should be available to urban water managers (Tate, 1990). Such possibilities contribute to the adaptability of cities and urban water utilities.

1.1 Urban Water Demand Management

The organization of cities can exemplify the problem of sustainable development. Cities exist, grow or decline through myriads of individual decisions and myriads of group decisions. And yet in spite of the human decisions, we don't say that cities are grown. We say that they grow. What makes a city unique is the spatial concentration. Because of spatial concentration of population and economic activity, cities have special problems. Jane Jacobs has called cities impractical.

Consider how impractical the cities of the fourth or fifth millennia B.C. must have become when their populations outgrew the water supplied by local streams and springs. No wonder the earliest engineering projects were water works. – Jacobs (1969)

A city is organized to solve the spatial problem, to bring resources flowing in at sufficient rate to maintain its organization or to grow. If it were not so organized, it would shrink and eventually cease to exist. Within the city, individuals and groups carry out functions which are subordinated to solving these problems. And yet the city's organization must accord with the needs and wants of people. To exist, the city must take materials and energy from its environment, which is always a place of uncertainty. Cities sometimes fail quickly, sometimes last for centuries. If they last long enough, they will certainly have their ups and downs. A city on its way up can in some sense be considered to be developing. Continuing to go up on and on, without at the moment stopping to consider what is meant by *going up,* would be to sustain development.

Urban water supply systems serve the purpose of the city's continued existence by providing water for household, industrial, commercial, and institutional uses. Urban wastewater systems serve the same purpose by removing wastewater, and waste materials transported by wastewater, from the city. The city is dependent on its environment, so it must not perturb that environment unduly. The water supply and wastewater systems must be operated with this in mind. These two systems require many types of resources for their operation. Reducing the flow of water through a city by means of demand management has potential for reducing the impact on the environment by taking less water from it. Also, fewer resources of other kinds would be needed to operate the water supply and wastewater systems. Demand management usually must be justified on economic grounds, using whatever current economic situation obtains. However, there are environmental benefits as well, resulting from the reduction in resource flows. The antagonism between present development and future development identified in the Brundtland Commission's report (World Commission on Environment and Development, 1987) seem at first to be absent.

Water demand management is one response to forecast growth in city water use. Often, forecasts of future water use are treated as supply requirements to be met (Hanke, 1978). This approach can be called *supply management.* In contrast to this approach, there is *demand management,* which seeks to modify the projections of water use. However, the terms *requirements* and *demand* are used in another way by Prasifka (1988). He states that forecasts using price are *demand forecasts,* whereas forecasts using other explanatory variables are *requirements forecasts.* The use of the word *requirements,* to me implies something which cannot be modified. Therefore, in this thesis, this term is rejected in favour of *demand* even when price is not used as an explanatory variable.

In this thesis, demand for water means an expected flow of water passing from a water producer to water consumers. The expected flows are predicted using a model which incorporates various explanatory factors. Price is a recognized and important determinant of such demand, and a demand curve, mapping the relationship between price and quantity demanded, represents a set of expected flows. In addition to demand for water, demand for wastewater removal is also treated as an expected flow. Factors affecting demand specifically for wastewater treatment are the proportion of consumptive use associated with a particular water use and the amount of inflow and infiltration into wastewater collection systems. Successful demand management measures will affect not only water supply planning for a municipality, but also wastewater treatment planning. It is therefore important to include wastewater treatment within the analytical boundaries when considering water demand management.

Water demand management is concerned with reducing demands for water supply and wastewater treatment. As such, it is similar to water conservation. According to Prasifka (1988), water conservation is "any beneficial reduction in water use or water losses." This is almost identical to the earlier statement, attributable to Baumann et al. (1980), that water conservation is "the socially beneficial reduction of water use or water loss." Tate (1990) emphasized that there may be situations where *socially beneficial* must be interpreted more broadly than is possible in benefit-cost methodology. For example, the benefits of reducing the water withdrawn from a river may possibly not be adequately expressed in monetary terms. Water demand management, in this thesis, means a socially beneficial reduction of water use or of water loss in the situation were there is differentiation between water producer and water consumer.

1.2 Sustainable Development

Sustainable development confronts society with two basic problems. The first is the problem of achieving the desirable societal characteristics. The provision of safe drinking water and the treatment of sewage-contaminated wastewater to control water-borne disease pathogens are examples of such goals. Most people would agree that these examples represent worthwhile benefits to humans. Less anthropocentric, more biocentric goals are also possible. There is apt to be less agreement about these. An example might be removal of nutrients from wastewater in order to protect a river ecosystem. Although it is hard to argue that this has no benefit to humans, from some viewpoints the cost might exceed the benefit. In any case, disagreements about and also changes in, the criteria used to define development must enter the picture.

The second basic problem is that of sustainability. This is the problem of continuing to meet criteria in the long-term despite changes in conditions. In the case of global human society, these include environmental changes, such as changes in resource availability, including those which result from development, or internal changes, such as technological innovation or organizational change. In the case of a geographically localized society, other environmental changes must be included as well. These are the changing influences of other localized societies. Such influences may be mediated through the natural environment, such as the downstream riparian influence of unassimilated wastewater. They may be mediated through economic activities related to comparative economic advantage. Economically efficient use of resources in providing water and wastewater treatment may be the best way that urban water systems can contribute in this sort of competitive situation.

The two basic problems, achieving societal goals and sustaining them, are interdependent. Striving for sustainability puts constraints on development, while development necessitates reformulation of the problem of sustainability by changing environmental and internal conditions. This is the dilemma of sustainable development (see Figure 1.1).

The situation is that there is a short-term bottom line and a long-term bottom line which usually do not agree. Wallerstein (1991) called this type of situation a *contradiction.*

Contradictions are the result of constraints imposed by systemic structures which make one set of behavior optimal for actors in the short run and a different, even opposite, set of behavior optimal for the same actors in the middle run.

Sustainable development is seen as a contradiction for which there are no ***in principle*** solutions. The long-term, frequently ecological, bottom line is equally as real as the short-term, frequently economic, bottom line. In principle, neither can take precedence over the other. In practice, resolutions to this contradiction are not only possible, but unavoidable, with outcomes of varying desirability. From these resolutions arise structural changes in the natural and socio-economic sectors of ecosystems.

Figure 1.1. The interaction between development and sustainability.

The importance of maintaining an adequate resource base and controlling pollution are generally recognized, if not always acted upon. Although such actions would not eliminate the contradiction between short-term and long-term, failure to do these things exacerbates the contradiction.

Defining water demand management in terms of social benefit, as was done above, leaves undefined whether or not the benefits are short-term or long-term. There is therefore room for contradiction between short-term and long-term which underlies the concept of sustainable development.

1.3 A Complex Systems Perspective

A city can be described in various ways. A description suitable for dealing with water as a commodity might be that a city is an economic system which has specialized system elements controlling the intake of water and the output of wastewater. But the water supply and wastewater treatment components of the city are more than economic. Because they are at the interface between the city and its non-economic environment, they have also an ecological character.

There has arisen fairly widespread support for what is called 'an ecosystem approach' to problems of sustainable development. Allen et al. (1993) have pointed out that there are many possible 'ecosystem approaches'. According to Mitchell and Shrubsole (1994), an ecosystem approach to sustainable development and environmental stewardship recognizes the need for a holistic, comprehensive, and cross-sectoral approach despite the existence of various agencies which might otherwise deal with issues in a fragmented way. This view of an ecosystem approach has become the general one (Kay et al., 1999; Kay and Regier, 2000). It is commendable as far as it goes, but it still treats ecosystems as though they were something separate from human societies. For a thorough-going ecosystem approach, it needs to be understood that cities and other economic systems are ecosystem components.[1]

The behaviour of socio-economic systems and ecological systems over time, i.e. their dynamic behaviour, has much in common. Socio-economic and ecological systems are open to flows of matter and energy, have hierarchical structure and in both of these types of systems structure is created and maintained through the dissipation of available energy (Conrad, 1983; Ulanowicz, 1986; Wicken, 1986; Dyke, 1988; Giampietro, 1997). The behaviour of such systems is characterized by the emergence of new structures and processes. System behaviour may at times be deterministic, at times deterministic within stochastic variability, and at times unpredictable and subject to sudden change. Catastrophe, in the sense of the word as it is used in catastrophe theory, refers to a

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[1] This view is far from original. "The Mecca of the economist lies in economic biology rather than in economic dynamics." – Marshall (1890), as quoted in Georgescu-Roegen (1971).

discontinuous change in some system variables in response to continuous change in other variables.[1] Chaos theory has shown that such discontinuities are fundamentally unpredictable, within constraints. General patterns of change may be predictable, but details are not. According to Simon (1990), the implications of chaos theory for the modelling of economic and ecological systems "have hardly begun to be digested". Such systems have been called 'self-organizing, dissipative systems', or SOHO (self-organizing holarchic[2] open) systems (Kay et al., 1999), or simply 'complex systems' (Wicken, 1986; Dyke, 1988).

In the dynamics of ecosystem behaviour, one of the general patterns of change is known as succession, or development. As an ecosystem develops, it goes through a phase of rapid, relatively inefficient growth, followed by a phase of slower more efficient growth. Development in effect ceases when the growth rate finally approaches zero. The fully developed, fully grown, ecosystem is far less resilient to external perturbation than a less developed, less grown ecosystem. Eventually a perturbation, external or internal, precipitates a crisis. Ecosystems therefore go through cycles of development and crisis. Holling (1986) has studied this phenomenon from the pragmatic viewpoint of environmental management, while Conrad (1983) has given it a theoretical basis with his *adaptability theory*. Development of the ecological type is unsustainable.

In the idea of ecologically sustainable economic development there is recognition that ecological considerations ultimately control human societies. It is therefore hard to see how

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[1] The word 'catastrophe', in this technical sense, has no associated value judgement. For example, the beating of a person's heart is caused by the repetitive building up of electrical potentials to catastrophe thresholds, at which points appropriate muscles contract.

[2] The term 'holarchic' derives from Koestler (1969). It is equivalent in meaning to the term 'hierarchical', as it is used in the natural sciences. 'Hierarchical' sometimes, but not always, has a somewhat different connation in the social sciences, which Koestler wished to avoid. See also the footnote on page 29.

the economic development process could be sustainable. An economic system cannot continue indefinitely on a stable course if the ecological system on which it depends periodically goes through crisis. Moreover, the same adaptability theoretic considerations which lead to instability in ecosystems should also lead to instability in economic systems (Conrad, 1983). According to this theory, economic development with an upper limit on the rate of material and energy throughput is a self-organizing optimization process in which the components of the economic system become more and more efficient[1] and the system as a whole less and less adaptable in the face of environmental and internal uncertainties. The only way to continue development without loss of robustness is to keep the economy growing. Limiting the size of an economic system, even if some way could be found to do this, to its long-term optimal scale, would eventually bring a short-term instability, or crisis, which would set back development to some earlier stage. Provided environmental conditions had not been compromised, development could then proceed from that stage, until the next crisis, and so on. From a practical point of view, it would be extremely important to know the spatial extent and severity of resulting crises, and also the length of time involved in any development-and-crisis cycle. From this point of view sustainability must include the notion of persistence through such cycles.

One of the notions about sustainable development is the importance of economic systems existing in balance with their environment. This means that input balances output, so that the environment is maintained in a state suitable for the continuation of the economic system. Such a notion implies a limit on economic growth. This idea is contained, for example, in the concept of the *steady-state economy* (Daly, 1977; Daly, 1990). Daly's idea is that a sustainable economy should function with its material inputs and outputs balanced so that it is not growing, with the result that its scale is fixed with respect to its

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[1] Efficient here does not refer to economic efficiency, but rather to 'efficiency' in its engineering or natural science sense. See Section 2.5.3 for a discussion of efficiency.

environment. Daly contends that neoclassical economics, the dominant school of economics for the past century, is incapable of dealing with issues of scale, since it deals only with allocation (of goods, services, and factors of production). In Daly's conception, economic development could continue in his steady-state economy even if growth did not. However, as noted above, the theory of development derived from the complex systems view of ecosystems does not support the idea of continued economic development in a no-growth economy.

1.4 Objectives and Scope of the Study

The major objective of this study is to identify the relationship between urban water demand management and sustainable development. The conventional view fails to capture the intricacies of the relationship between demand management and sustainable development because it does not apply a complex systems approach to the issue of economic development.

The conventional view appears to be the following. Water as a commodity is used in various ways in cities, and is necessary for the economic development of the city. Economically justified demand management strategies help to ensure that water demands are met. Such strategies serve the economic development of a city. At the same time, these strategies reduce the use of water, and also the use of other resources needed by the water utility. Reduction in the use of water and other resources lessens the impact of the city on the natural environment, thus enhancing sustainability.

The difficulty with the conventional view is that it does not place economic development in the larger context of ecosystem processes. From a complex systems perspective, it can be seen that economic development has certain propensities which render it unsustainable. Water demand management helps to further economic development by pushing back barriers to growth. The conventional view assumes that development can be sustained provided things are done right. It does not seem to consider the problem of what to sustain if development fails.

An ecosystem approach is often advocated for problems of environmental management and sustainable development (Allen et al., 1993; Mitchell and Shrubsole, 1994; Kay et al., 1999; Royal Commission on the Future of the Toronto Waterfront, 1992; Slocombe, 1993). In the case of urban water systems, this has typically led to an ecosystem approach only for the assessment of the impacts of urban water and wastewater systems on the natural environment.

Emerging ecological theory uses complex systems theory to understand ecosystems (Kay, 1984; Schneider and Kay, 1994b). Socio-economic systems also are regarded as complex systems (Wicken, 1986; Dyke, 1988; Giampietro, 1997; Kay and Regier, 2000). Furthermore, socio-economic systems are viewed as being situated within ecosystems: they are complex system components of complex systems. The behaviour of complex systems is frequently unpredictable in detail. Nevertheless, there is much that complex systems theory can say about the general trends in such systems. A complex systems approach was applied to the qualitative analysis of the contribution of urban water demand management to sustainable development.

This dissertation in part deals with demand management in the Regional Municipality of Waterloo, in southern Ontario. In the complex systems approach to sustainability, as in other approaches, it is necessary to decide what is to be sustained. In the Regional Municipality of Waterloo, a community vision of sustainability has been produced as part of the Regional Official Policies Plan (Regional Municipality of Waterloo, 1998). This vision statement was used in this study to provide criteria for sustainability. At a larger geographic scale, the Grand River Conservation Authority (GRCA) co-ordinated a process for determining a vision of sustainability for the Grand River watershed (Grand River

Conservation Authority, 1998).[1] This is the watershed within which the Regional Municipality of Waterloo is situated. The GRCA report constituted a second source of criteria for sustainability for this study. The wise use of water and the practice of urban water demand management were endorsed as strategies for sustainability in both these reports.

The Regional Municipality of Waterloo is regarded as a leader in urban water demand management in Canada. In the course of this study, certain problems relating to the implementation or proposed implementation of demand management measures in the Regional Municipality became apparent. Analysis of these problems provided additional objectives of this study. Three specific problems were addressed.

(1) The Regional Municipality of Waterloo had undertaken two planning studies, one for water supply and one for wastewater treatment. Although water demand measures were proposed in their water supply planning study, it was apparent that demand management could have been better integrated within the water supply planning study and better integrated with the wastewater treatment planning study. An analysis was performed which illustrated a process by which integration could be achieved and the benefits to be derived from integration.

(2) The Regional Municipality of Waterloo forecasts water use without taking into account the effect of price on water use. One method which the Region uses to avoid large jumps in price is price smoothing. Price smoothing is used by Regional staff only for this purpose. However, if prices are smoothed upwards in anticipation of future increased costs, demand for water could be reduced, thereby deferring capital costs. However, this effect could only be shown if the relationship between price and demand

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[1] These two visions statements are reproduced in Appendix B.

was accounted for. A simulation model was constructed which shows the effects of anticipatory price smoothing while simultaneously forecasting water use and price.

(3) A pricing structure for water, known as summer use pricing, was under consideration by the Region. Water use increases for many water customers in summer. With summer use pricing, a customer's basic level of water use is defined by his water use in winter. Additional water use occurring in summer can then be calculated for the customer by subtracting basic water use from total summer water use. Basic water, even that occurring in summer, is charged at one price; the additional summer water use is charged at another, higher price. The problem is that it is possible for a customer to waste water deliberately in the winter in order to obtain more water in summer at the lower price. An analysis was performed to determine how to avoid this problem by appropriately setting the price differential and other parameters.

In summary, the main objective of this study is to establish in general terms the relationship between urban water demand management and sustainable development. Two vision statements were used as sources of criteria for what to sustain. These statements pertained to sustainability in the Regional Municipality of Waterloo in the Grand River watershed in southern Ontario. The analysis of three local and specific problems of demand management in the Regional Municipality of Waterloo were subsidiary objectives of this study.

1.5 Organization of the Thesis

The dissertation deals first with the theme of how urban water demand management relates to sustainable development from a complex systems perspective, then proceeds to the second theme, which deals with specific practices and strategies of demand management.

Chapter 2 introduces ecological economics, complex systems theory and urban water demand management.

In Chapter 3, development is described as a process which occurs in complex, dissipative systems. The description includes implications for sustainability.

Chapter 4 gives a qualitative assessment of the relationship between urban water demand management and sustainability, from the point of view of the theory of development presented in Chapter 3.

Chapter 5 reports on the case study of integration of demand management with water supply planning and wastewater treatment planning in the Regional Municipality of Waterloo in Ontario, Canada.

In Chapter 6, a model is presented which outlines a methodology for price smoothing, while forecasting demand and price simultaneously.

Chapter 7 takes up the issue of deliberate water wastage with a summer use pricing structure.

Chapter 8 summarizes conclusions, contributions of this work and gives possible directions for future research.

2

Background

This chapter presents economic development as a problem-solving activity in which the goal is to improve or maintain human well-being. This is called 'development by design'. If development is to be sustainable, long-term goals must not sacrificed for short-term goals (see Figure 1.1).

Development is undertaken in the context of socio-economic systems and the ecological systems which form their environment. A complex system view of ecological systems, economic systems and their interaction is needed to supplement traditional ecological and economic thinking on development. A complex systems view of economic systems differs substantially from the traditional view of neoclassical economics. Although it is beyond the scope of this thesis to explore these differences exhaustively, they are highlighted here.

The role of urban water utilities involves continuous problem-solving in the provision of water and wastewater services. Water demand management can be part of this problem-solving activity. Different demand management methods are briefly surveyed here.

2.1 Development as Problem-Solving

When people speak of economic development, they generally mean some sort of change which is beneficial in terms of meeting their needs, or bettering their standard of living. Sometimes, the word development is used to refer to a specific social project, as in the following:

the modification of the biosphere and the application of human, financial, living and non-living resources to satisfy human needs and improve the quality of human life. - International Union for Conservation of Nature and Natural Resources (1980)

However, in this study economic development is considered to be an ongoing process, consisting of a stream of such projects.

Development by design can be viewed from the standpoint of problem-solving. A problem situation exists when there is a gap between an actual situation and a more desirable, but potential, situation. At its most basic, problem-solving involves a mental model as a guide to action, as shown in Figure 2.1. Usual usages of the word problem indicate that there should be some degree of difficulty attached to the mental model. The mental process is therefore often augmented by suitable tools (pencil and paper, computer) and techniques (diagrams, mathematical modelling). Action results in a transformation of the actual situation in some way, presumably in the direction of closing the gap. However, the gap is not necessarily made smaller. This is to say that problem-solving may fail. However, it seems reasonable to call the process problem-solving in any case.

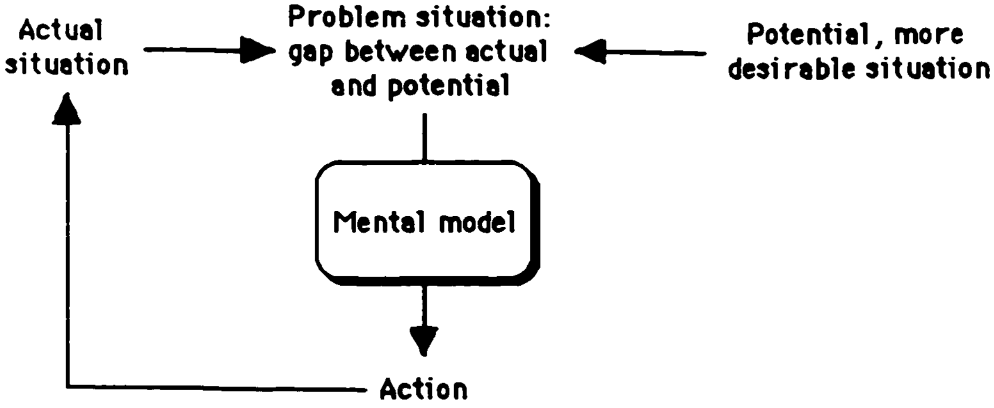

Figure 2.1. Problem-solving. A representation inspired by Senge (1990) and High Performance Systems (1997).

Development, then, involves problem-solving which has as its goal the improvement of (or maintenance of) desirable human living conditions. Development results from the successful solving of this type of problem. Unlike generalized problem-solving, then, development may not fail if it is still to be called development. Sustainable development therefore seems to imply a process resulting in a continuous stream of successes. This implication is extreme, something which has been recognized by Turner and Pearce (1992). They give the term *strong sustainability* to the situation where gains are being made for each and every time period. The situation where gains are not necessarily made in every time period, but only the general trend is positive, they term *weak sustainability.* In their judgement, weak sustainability is more realistic than strong sustainability.

It is argued by Tainter (1988) that societies are always engaged in collective problem-solving, and their chief strategy is complexification. However, complexification requires increasing energy use. As complexification progresses, it is rewarded by diminishing returns. At some point, increasing complexification causes the society to collapse. The only way to avoid this is to find new energy subsidies. Tainter's background is archaeology and sociology, but his conclusions agree quite well in general form with the complex system description of development presented in the next chapter. However, he omits consideration of environmental uncertainty, which, along with energy availability, is another important determinant of the usefulness of complexification.

A view such as Tainter's would imply that even the weak sustainability of Turner and Pearce is not possible in the long run, unless energy supplies are continuously expandable. It is this understanding which has led many to reject the term 'sustainable development' in favour of the term 'sustainability'. However there is much confusion on this point, with 'sustainable development' and 'sustainability' used interchangeably by many authors. Note that Turner and Pearce (1992) were definitely speaking of sustainable *development,* even though they use the term *sustainability.* The term 'sustainability', as distinct from 'sustainable development', was defined by Robinson et al. (1990). For them, sustainability is the "persistence over an apparently indefinite future of certain necessary and desired characteristics of the socio-political system and its natural environment." The "necessary and desired characteristics" are in effect design criteria for the 'potential, more desirable situation' of societal problem-solving. The problem-solving of sustainability is in some sense solving the problem of staying in existence[1], within certain design criteria of social desirability.

2.2 Ecology and Economics

Theories of how economic systems work and how ecological systems work should be of value in solving the problems of development. Development by design is carried out in a complex societal setting where many participants have roles to play. Economic systems obtain raw materials and energy from their environments and return waste products to their environments. So, like any other biological species, humans exist in an ecological setting. Traditional ecology and traditional economics have not dealt well with the links between economic systems and ecological systems. Due to expanding human populations, pollution, depletion of non-renewable resources and stresses on renewable resources, the need for understanding the links is growing.

Ecologists tend to emphasize the natural, i.e. non-human, subject matter of their discipline. When ecologists do include humans in ecosystem studies, the inclusion is often limited to strictly biological aspects such as reproduction or nutrition, or to effects of economic activities, such as pollution or habitat destruction. This view expressly excludes economic activities themselves from ecology. On the other hand, economists tend to view the natural world mainly as a source of benefits and costs external to the economic system

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[1] This has been called the existential problem (Conrad, 1995), or the existential game (Slobodkin and Rapoport, 1974).

proper. The importance of externalities is generally recognized in environmental economics, and economic methodology is being expanded to deal with them. Nevertheless, extra-economic knowledge is required to understand the processes at work which create these externalities.

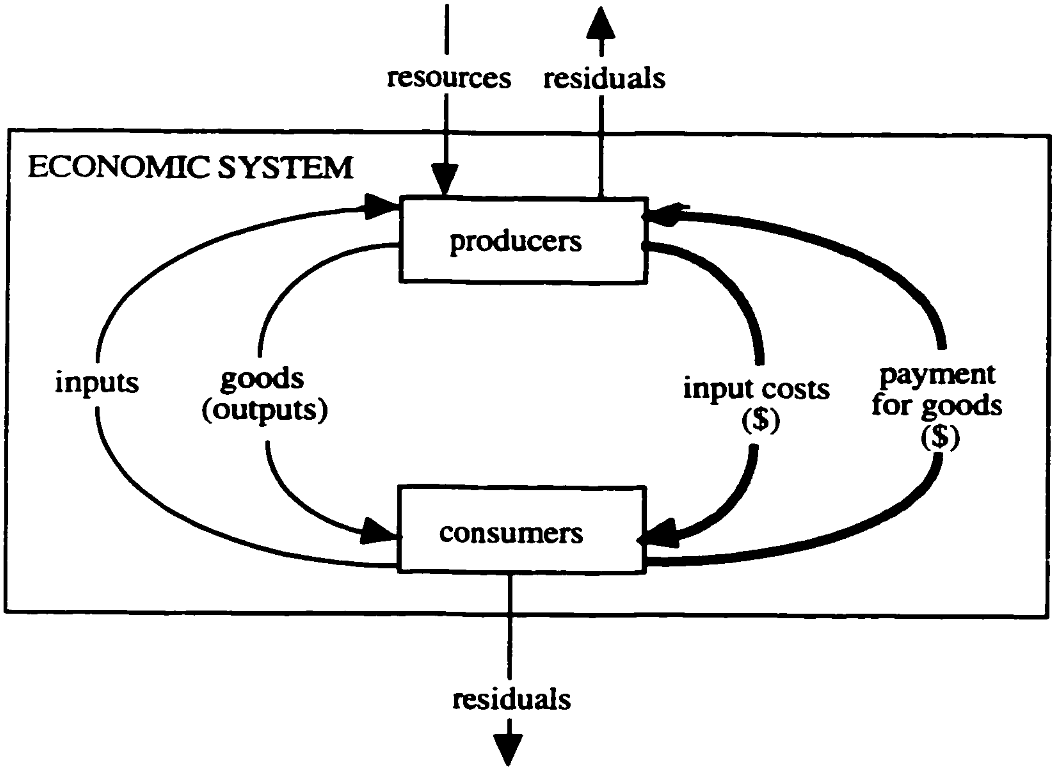

Figure 2.2. A conventional economic system, with an internal circuit of value (thick lines) and throughput of material (thin lines).

Economics is the study of the human allocation of scarce resources to alternative ends. Economics typically deals with economic agents who are not self-sufficient for their needs and wants (the usual situation), and who consequently must trade from what they have to get what they want. This is the general situation, which is conventionalized to a dichotomy between producers and consumers (see Figure 2.2). An economic system takes flows of resources from its environment, and contributes flows of residuals to its environment. Within the system, there is a circular flow of economic value. Depending on how boundaries are drawn between economic systems, there can be flows of goods and economic value from and to other economic systems. In other words, the environment of an economic system may include not only the natural environment, but also other economic systems. Trade links to other economic systems are not shown in Figure 2.2.

Ecology tries to explain the distribution of populations of organisms, and the flows of energy and materials among organisms, and between organisms and their environments. One of the central concepts of ecology is the ecosystem. An ecosystem is a portion of the earth's surface bounded in some way, even if only conceptually. It consists of the system of organisms and their non-living surroundings contained within the boundary, interacting through the transfers of energy and materials within the ecosystem and across the ecosystem boundary. Some ecosystems contain humans. The living part of the ecosystem, the biota, has a hierarchical organization. For example, the biota can be divided into levels of organization: the biota contains populations of particular species, the populations contain individuals, the individuals contain organs, and the organs contain cells.

The main features of material and energy flow in an ecosystem which contains an economic system are shown schematically in Figure 2.3. I will adopt Conrad's useful term 'economic ecosystem' for an ecosystem which contains humans (Conrad, 1983). An ecosystem maintains its complex hierarchical structure by converting inputs of high quality energy to outputs of low quality energy. Plants capture high quality energy in the form of sunlight and convert it to maintain themselves and to grow. Herbivorous animals 'capture' plants for the same purposes, and so on. This is the ecosystem process. It requires a steady source of raw materials, so decomposers (bacteria, fungi) are needed to return spent materials to the non-living portion of the ecosystem. From there, materials can be taken up by plants again. If the biota of an ecosystem is not at least on average in material balance with its environment, it must change because the ecosystem flow processes cannot continue unaffected. Change may occur at any level of hierarchy. There may be changes in species presence and absence, population sizes, sizes of individuals, physiological processes, or gene frequencies. Cycling of materials can be tight or leaky, depending on the amount of exchange across the ecosystem boundary.

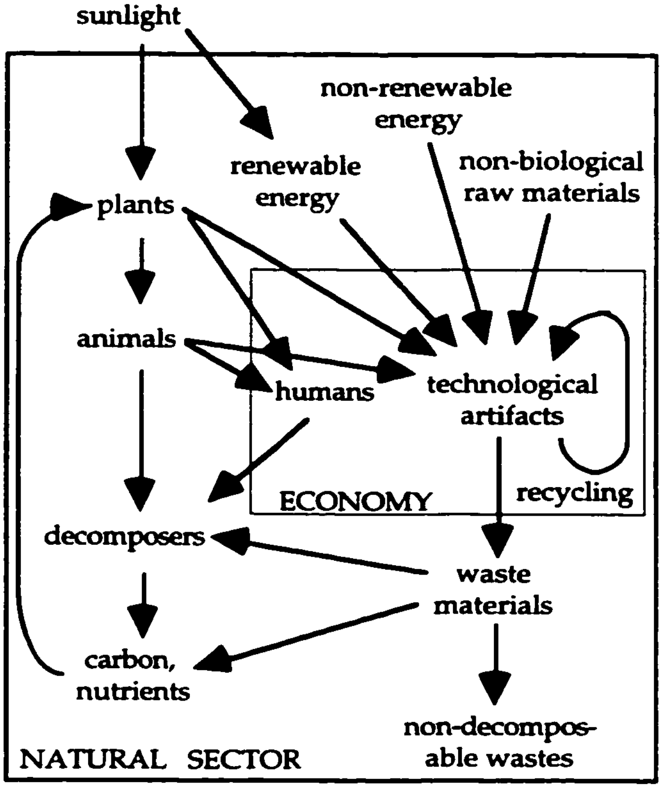

Figure 2.3. An ecosystem divided into an economy and a natural sector, showing the flow processes.

Economic systems are open systems: matter crosses their boundaries. The inputs to an economic system are raw materials from its natural environment and produced goods from other economic systems. Within an economic system, production and consumption transform the inputs into waste, tradable goods, and human bodies. The flow processes are indicated in Figure 2.3, where for diagrammatic simplicity, the ecosystem has no material interchange with other ecosystems. Because the ecosystem in Figure 2.3 is closed to material transfer, it could represent the world ecosystem. The part of the ecosystem not within the economy can be called the natural sector of the ecosystem, while the economy, or economic system, can also be called the economic sector of the ecosystem.

The newly recognized field of ecological economics attempts to bridge the gap between ecology and economics by expanding the areas of overlap between them (Costanza, 1989). Ecological economics is usually considered a new field. According to Martínez-Alier (1987), it was given impetus and the appropriate sociological conditions for developing as an academic discipline by the energy crisis of the 1970s. However, analysis of economic systems from an ecological viewpoint began in the 1880s, when it first became possible to apply the newly formulated laws of thermodynamics to economic systems. According to Martínez-Alier, two of the first were Podolinski (1880-3) and Sacher (1881). Because their work prefigured most of the main subsequent themes of ecological economics, it bears closer examination.

Podolinsky determined that a human society must gain an energy output at least twenty times its energy input in the form of labour in order to perpetuate itself. This number represents a subsistence level economy, where the energy gained through labour is primarily the chemical energy of food. Sacher independently arrived at the same estimate, but went on to try to correlate stages of cultural development with energy availability. Sacher raised the issue of an energy theory of economic value, in which the economic value of commodities and services was determined wholly or in part by the energy required for their production. He attempted to devise an elaborate model for explaining prices of commodities by means of their energy input, but in the end he had to acknowledge that his model didn't work. Podolinski raised the issue of an energy theory of value, but only for the purpose of rejecting it, without giving his reasoning for doing so.

The issues raised by the work of Podolinski and Sacher which are still current topics in what is now called ecological economics are: 1) the requirement for a sufficient energy rate of return for the energy expended in human labour; 2) the relationship between energy availability and different levels of cultural or economic development; 3) the issue of reduction, or the impossibility of reduction, of economic behaviour to biological and physical terms; and 4) a tendency to include humans inside the description of economic systems.

A modern example of the latter tendency is found in Ruth (1993): "The economic system is defined typically as a system of humans and endowments of material stocks, energy flows and technologies, organized according to a social system of institutions that guide the production and consumption of goods and services."

2.3 Equilibrium in Economic and Ecological Systems

Economic equilibrium is one of the most important concepts of neoclassical economics. In ecology, equilibrium theories were in vogue at least for the first half of the twentieth century. These theories have now mostly given way to the realization that although equilibrium may be reached, it is unstable.

Market exchange in an economic system can be generalized by exchange between firms, or producers, and households, or consumers. This is illustrated in Figure 2.2. Households buy goods from firms, and firms pay households for labour. Circulation of exchange value, represented by the arrows with $ signs in Figure 2.2, is closed within an economic system. Production of goods and services can be described by a production function, which relates the cost of inputs to quantity of goods produced. Consumption can be described by a demand function, which relates the price of goods to the quantity demanded. By the 1870s, Walras thought that such a closed system would have an equilibrium set of output flows and prices (Ayres and Kneese, 1989). Based on an axiomatic approach, the existence of equilibrium was given mathematical proof by Arrow and Debreu (1954). According to neoclassical theory, when an economic system operates at equilibrium, net benefits to society are maximized.

Several conditions are required to be fulfilled for general equilibrium to exist. One of these is perfect knowledge of markets by all economic actors. Ayres and Kneese (1989) argue that the neoclassical model is 'fatally flawed' because of the necessity of technological change in real world economies. Readily available resources are used up and others are introduced as substitutes. What enables this substitution process is technological change. Since technological change is not a predictable process, it always introduces uncertainty inconsistent with the theoretical requirement for perfect knowledge. Schumpeter (1943) made the same point in a different way. According to him, the type of perfectly competitive market does not and cannot exist because economic systems are evolutionary. That is to say that competition takes place through innovations (new products, new services, new organizational structures) whose aim is to ensure a continual stream of short-term monopolies.

Lombardini (1989) makes this point, too, but also two others. The first is that neoclassical economics takes the preferences of consumers as given, so that there is no possibility of considering feedback between market processes and preferences. The other is that production and consumption involve processes which are external to the economic system. These external processes are those which cause resource depletion and pollution.

Given the high rate of innovation possible in a growing economic system, equilibrium may never be seen. In contrast, it may take decades or even hundreds of years for an ecosystem to reach equilibrium. The equilibrium situation in an ecosystem is called the climax ecological community, and the long process of getting to it is called succession. In succession, one set of species creates conditions inimical to its own survival, and beneficial to the next set of species, which succeeds the first set. The process of replacement continues until there is a set of species which can reproduce and maintain itself without being replaced (Odum, 1971).

The principles of economic equilibrium were established without reference to the flow of materials and energy through an economic system. Only the internal circulation is captured in the formulation of economic equilibrium. In contrast, ecology has always been concerned with the flow of materials and energy through an ecological system. So the process of succession is not just the equilibration of the populations of various species of organisms. It also involves the establishment of equilibrium in material transfer between the living, organismic part of the ecosystem, and the non-living parts (minerals, water, etc.). This is theoretically necessary if equilibrium is to be established, and the tendency has been shown empirically. The fact that the tendency is never perfected in real ecosystems is one of the sources of instability at equilibrium. Equilibrium between the living and non-living parts of an ecosystem is called balance. Unless there is balance, the ecosystem must keep changing (Conrad, 1983), although the pace of change in ecosystems which have achieved near-balance can be extremely slow.

Current economic ecosystems are not in ecological equilibrium. The use of non-renewable resources means that balance cannot be achieved. This is an observation, not a judgement. The expanding human populations and declining populations of some other species shows that there is also no equilibrium with respect to populations. It is impossible for economic systems in these circumstances to achieve equilibrium in the ecological sense. Therefore modern economic systems must, and do, keep changing. For this reason, the applicability of economic general equilibrium theory, with its requirement for a *given* set of production processes and a *given* set of demand functions, should be limited to the short time frame in which these conditions remain approximately true.

In the book, "Limits to Growth", Meadows et al. (1972) shocked the world with their prognosis for the future of the world economic system. They predicted that if growth in human population and industrial activity increased exponentially, resources would be exhausted, leading to rapid declines in the twenty-first century of both population and industrial activity. In effect, they highlighted the lack of ecological equilibrium between the current world socio-economic system and its environment. They devoted a chapter to advocating a transition of the present 'growth economy' to a 'global equilibrium'.

Economist Herman Daly also views a global equilibrium as desirable (Daly, 1977; Daly, 1996).

A complex systems theory of development in ecosystems suggests that such an global equilibrium would not be stable. A complex systems perspective is introduced in Section 2.5, but a full description of development as a complex systems process is deferred to the next chapter.

2.4 Efficiency

Two definitions of efficiency are needed in this thesis. One concept is that in common use in engineering and the natural sciences. From an engineering perspective, it could be called 'technical efficiency'. However, the concept is widely used in non-engineering situations as well, where the word 'technical' would not be appropriate. In this thesis, it will be called simply 'efficiency'. The second concept is that used in economics. This will be called 'economic efficiency'.

The concept of technical efficiency gives the quantitative yield of an output to a process in relation to the quantity of an input. Ordinary efficiency is then:

$$\eta \equiv \frac{\text{output}}{\text{input}}$$

Generally, processes may have more than one output and more than one input. Efficiency normally considers a selection of output and input. Only an output of interest, and an input, or inputs, of interest are considered. An example can be given with respect to the energy analysis of a process. Provided there is no accumulation of energy in the process, output must equal input. This is in accordance with the first law of thermodynamics. First law efficiency will always be 100%, which is not a very interesting result. It is more interesting to select only useful work from among the energy outputs.

In the water demand management context, goals are sometimes stated in terms of water use efficiency. For example, it may be an objective to replace 12 L flush toilets with 6 L flush toilets. The water efficiency of an entire city could perhaps be expressed as the water use per capita. Simply decreasing the water use per capita may be a desirable goal from the point of view of decreasing the environmental impact of the city. However, at some point decreasing per capita water use will be incompatible with sustaining the economic livelihood of the city, not to mention the well-being of the people who live there.

Neoclassical economics uses a different idea of efficiency. According to theory, the free operation of a perfectly competitive market will yield an allocation of inputs to production processes and outputs from production processes which is said to be efficient. The efficient allocation is one in which Pareto optimality holds with respect to market participants, i.e. when no participant in the market can be made better off with a different allocation without making some other participant worse off. Efficient allocation occurs when net benefits, i.e. benefits minus costs, are maximized. Benefits and costs are expressed in terms of economic value, not in terms of physical quantities.

Accepting, as I do, the evolutionary propensities of economic systems, and their ability to cause changes in the environmental conditions in which they operate, economic efficiency seems to be a worthwhile design choice only for the short-term goals. Dyke (1988) emphasized the short-term nature of economic efficiency in the following way:

> *...the "efficient" equilibrium is a function of the short-range interests and perceptions of a population of the moment. Since any long-range economic policy would* budget *resources over a long period of time, either the momentary equilibrium is irrelevant, since on the usual assumptions market participants have no reason to aim at long-run efficiency, or we have to suppose that the long-range budget is serendipitously in accord with the short-range budgets of the participants in the market equilibrium. The latter supposition is bizarre.*

Dyke comes out strongly in favour of long-term efficiency, as opposed to short-term economic efficiency. I would prefer to keep both sides of the short-term / long-term contradiction of sustainability firmly in mind. For example, the financial viability of urban water supply systems requires that at least some decisions be made with a short-term perspective. Water rates are set once per year; planning periods must be for only a few years due to the difficulty of achieving accurate forecasts for longer periods. The short-term / long-term contradiction is a true dilemma.

2.5 A Complex Systems Perspective

One of the bases for a complex systems perspective is the idea of *system*. Gordon (1969) defines a system as "an aggregation or assemblage of objects joined in some regular interaction or interdependence". Another definition is: "an assembly of elements related in an organized whole" (Flood and Carson, 1988). In the process of defining a system, a boundary is selected which circumscribes the extent of the system. Defining a system *type* sets a boundary of another kind (Allen et al., 1993). System type is defined in terms of a selection of relevant attributes of system elements and of types of relationships between elements. An urban water system and an urban road system could have the same physical boundaries, but they are different in type. Outside the boundary of the system is its environment.

If an investigator has defined a system in an advantageous way, the density of connections between system elements will be relatively high, while the density of connections between system elements and the system's environment will be relatively low (Flood and Carson, 1988). A system with this property will behave with a degree of independence from its environment. This is of course what makes it possible to identify a system as a separate entity. A system can be made up of similarly identifiable subsystems.

With a change of perspective, each subsystem can be called a system. These may also be composed of subsystems.

This is one the features of complex systems: they consist of systems within systems at many levels. This is what is meant by a hierarchical[1] system. Simon (1962) showed that hierarchical organization allows a self-organizing system to evolve at a faster rate. Conrad (1983) provided a definition of independence between hierarchical levels and between subsystems within hierarchical levels, and showed that independence of subsystems enhances the adaptability of the system to an uncertain environment. Biological systems and socio-economic systems are hierarchically organized. Populations are composed of individuals, individuals are composed of organs, organs are composed of cells, and so on. Socio-economic systems are composed of individuals organized into families, firms, and other organizations. An analysis based on complex systems thinking must consider more than one temporal and spatial scale. Complex systems thinking is thus suitable for the analysis of the contradiction inherent in sustainable development.

Self-organization refers to the spontaneous appearance of new processes stabilized in new structures. It occurs when high quality energy is input into an open system. This moves the system away from thermodynamic equilibrium. The new processes which appear are the system's mechanism for resisting movement away from thermodynamic equilibrium. The system is therefore not moved so far from equilibrium as it would have been if the processes had not appeared. Also, more high quality energy is converted to low

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[1] There are problems with the word 'hierarchical' because of its different usages. The above 'box-within-box' usage of the word 'hierarchical' seems to be typical of the natural sciences. The idea of dominance of lower level by higher levels within a hierarchy is not intended; influence can flow in either direction. In the social sciences, the idea of dominance is often present, sometimes by higher levels influencing lower levels, sometimes by dominant members of one level influencing other members of the same level. This last is closest to the original meaning of the word.

quality energy, or dissipated,[1] than would have happened had the processes not appeared (Schneider and Kay, 1994a; Schneider and Kay, 1994b). The earth's surface is a system which receives an input of high quality energy, in the form of sunlight. One result is that weather patterns emerge in the atmosphere. These patterns exhibit organization but are nevertheless unpredictable in detail. Another result was the emergence of living organisms.

The appearance of new processes, with associated structures, takes place in a sequence of rapid stepwise changes, interspersed with periods of relative stability. The living world did not suddenly appear full blown in its present state. With each stepwise change, there is an increase in the ability of the self-organizing system to dissipate the high quality energy input. According to recent developments in non-equilibrium thermodynamics (Schneider and Kay, 1994a; Schneider and Kay, 1994b), as systems become more organized, they become better able to capture high quality energy in order to dissipate it. Economic development in the West over the past two hundred and fifty years has followed this path, with more and more effective dissipation of more and more stocks of high quality energy, accompanied by a higher and higher level of socio-economic organization.

The theory of development of complex systems has important implications for socio-economic systems. Stocks of non-renewable natural resources are being depleted (on the depletion of oil, see Subsection 4.3.3). This will at some point require a return to socio-economic systems which run on solar energy alone, which means a reduction in scale of socio-economic activity. The production of pollution and other wastes, a process necessary for the stabilization of economic systems far from thermodynamic equilibrium, is another contender for limiting the scale of economic operations. Therefore, the idea of

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[1] Dissipation refers to the product of temperature and rate of irreversible entropy production in a system. It has the dimension of power, i.e. energy per unit time. The entropy of an open system may also change reversibly through the movement of matter across its boundaries.

limited scale of economic activity, coupled with continuing economic development, has its appeal. However, a theory of development derived from the complex systems view of ecosystems does not support the idea of continued development coupled with limited scale. As an ecosystem develops, it goes through a phase of rapid, relatively inefficient growth, followed by a phase of slower more efficient growth. Development in effect ceases when the growth rate finally approaches zero. The fully developed, fully grown, ecosystem is far less resilient to external perturbation than a less developed, less grown ecosystem. Eventually a perturbation, external or internal, precipitates a crisis. Ecosystems therefore go through cycles of development and crisis. Holling (1986) has studied this phenomenon from the pragmatic viewpoint of environmental management, while Conrad (1983) has given it a theoretical basis with his *adaptability theory*. Development of the ecological type is unsustainable.

The same adaptability theoretic considerations which lead to instability in ecosystems should also lead to instability in economic systems (Conrad, 1983). According to this theory, economic development with an upper limit on the rate of material and energy throughput is a self-organizing optimization process in which the components of the economic system becomes more and more efficient[1] and the system as a whole less and less adaptable in the face of environmental and internal uncertainties. The only way to continue development without loss of robustness is to keep the economy growing. Limiting the size of an economic system, even if some way could be found to do this, to its long-term optimal scale, would eventually bring a short-term instability, or crisis, which would set back development to some earlier stage. Provided environmental conditions had not been compromised, development could then proceed from that stage, until the next crisis, and so on.

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[1] Efficient here does not refer to economic efficiency, but rather to 'efficiency' in its engineering or natural science sense. See Section 1.3 for a discussion of efficiency.

2.6 Urban Water Systems and Demand Management

An urban water system for the purpose of this study is concerned with urban water as a commodity. Stormwater, not being a commodity, is outside the scope of this thesis. A water utility *produces* water, i.e. it converts water as an environmental resource into water as a commodity. The water will come from one or more sources, and will be treated, perhaps differently depending on the source, before it becomes a commodity. Distribution of water is usually also an important part of the utility's function. Often (in Ontario) the same utility is mandated to collect wastewater and treat it before releasing it back into the environment.

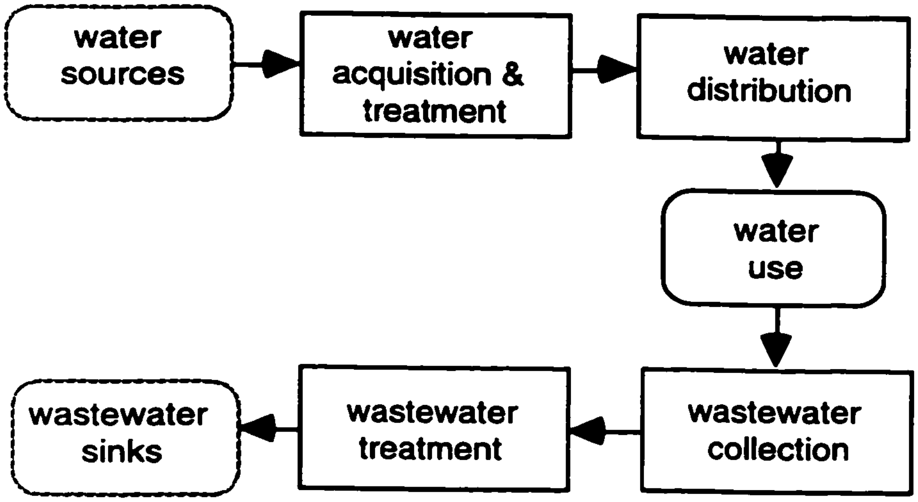

Figure 2.4. The urban water system. Solid boxes are system components, dotted boxes are water sources and wastewater sinks. Rounded rectangular compartments are outside direct managerial control.

An urban water system, then, consists of several essential components: water supply and water distribution subsystems, a water use subsystem, and wastewater collection and treatment subsystems. Outside the urban water system, the environment is represented by the sources from which water is acquired and sinks to which it is returned after use. These features are shown in Figure 2.4. The subsystems of Figure 2.4 could themselves be divided into further subsystems. For example, the water use subsystem could divided into two categories: residential and non-residential. Such a division could be useful for forecasting: water among residences is fairly uniform, while non-residential water use is less so. Industrial water use, for example, will depend greatly on what industries are present. The viewpoint taken in this thesis was that of a municipal water manager who does not have control over the water use portion of the system of Figure 2.4, but who can take some action to influence it.

In the Regional Municipality of Waterloo, Ontario, the Master Water Supply Study of 1987 (Dillon, 1987) used population and per capita water use exclusively and the current Long Term Water Strategy (Associated Engineering, 1994) used population and per capita water use for forecasting all water use in the rural townships, but only for residential water use in the cities. In the cities (Kitchener, Cambridge, and Waterloo) the Long Term Water Strategy disaggregated water use in residential, industrial, commercial, and institutional sectors. Population was used as the explanatory variable for residential water use, but land area was used for industrial, commercial, and institutional water use in the cities. Boland et al. (1981) reported that forecasting with a the single explanatory variable, or its disaggregated versions, were the predominant forecasting methods in the 1960s and 1970s.

It is evident that reduction of urban water throughput could play some role with respect to reducing the scale of a city's impact on its natural environment. However, it is also true that in geographical areas where water is plentiful, it seems likely that a resource or resources other than water would be more important in determining the appropriate scale of economic activity.

In the Regional Municipality of Waterloo, water supply and wastewater treatment are services of the Regional Municipality, while water distribution and wastewater collection are the responsibilities of the local municipalities within the Region. Responsibility for water use, of course, resides in numerous homes, businesses, industries, and institutions situated within the Region. Where this study looks at the specific case of the Regional Municipality of Waterloo, it does so from the Regional point of view.

2.6.1 Forecasting Water Use

The prevailing situation with respect to urban water is that there is pressure to increase water supply, whether sooner or later. This situation is due to continuing growth in the populations and the economic activities of cities, so that there is increasing demand for residential and non-residential water. Forecasting the demand for water is an important part of urban water system management. In a discussion of water demand forecasting, Prasifka (1988) refers to forecasting methods with single explanatory variables, as well as to less common methods with more than one explanatory variable. The most common method uses a single explanatory variable, population. Of course, exogenous forecasts of population must be available. The model in general use links water use to population by means of a single coefficient.

$$Q = a\,P \qquad \text{eq. 2.1}$$

In equation 2.1, Q is water use, P is population, a is the linking coefficient, with the dimension *water use per capita*. The next most common single explanatory variable is the number of customer connections (Prasifka, 1988).

In spite of the prevalence of forecasting with only one explanatory variable (and one coefficient), many factors influence urban water use. A list of these has been compiled by Prasifka (1988). This is given in Table 2.1.

Table 2.1. Factors which Influence Urban Water Demand (from Prasifka, 1988)

Demographic:

- population
- housing density
- type of housing
- household size
- construction grading
- size of lot
- irrigated area
- connections to public sewer
- recreation lake

Economic:

- income level
- assessed sales value of residence
- water-rate structure and price level(s)
- employee productivity

Sociopolitical:

- consumer preferences, habits and tastes
- legal and political constraints
- cultural constraints or incentives
- consumer education
- policy variables

Climatic:

- temperature
- precipitation
- moisture deficit
- implementation of drought-tolerant landscaping

Technological:

- input of raw materials
- water recirculation rates
- inspection and repair of faulty plumbing
- leak-detection program
- efficiency of water-using equipment
- distribution pressure
- supply dependability
- allocation of water of different quality to different users

2.6.2 Demand Management

This study focuses on demand management as a means for increasing the sustainability of urban development. However, there are many possible reasons for water demand management. Robinson (1986) gave the following reasons, most of which apply to urban water systems:

- inavailability of short-term supply, e.g. due to drought
- long-term inadequacy of supply, due to rising population or increasing agricultural usage
- protection of natural aquatic habitats
- social, political, and institutional obstacles to increasing water supply
- cost saving
- inflation of population forecasts
- public demand for demand management

Tate (1990) gave promotion of sustainable development as a reason for demand management, but also set out the following:

- larger selection of alternatives for water management
- cost reduction
- energy savings
- reallocation of resources to other segments of society
- greater social equity
- less environmental impact

In addition to these reasons, there is some evidence to suggest that the performance of wastewater treatment plants improves with the higher waste concentrations which result from reduced water use (Hydromantis, 1993).

There are many possible mechanisms of water demand management in cities. The following brief survey was compiled from Flack (1982), Robinson (1986), Maddaus (1987), Prasifka (1988), and Tate (1990). Water demand management methods were classified by Flack (1982) into four categories which are used in the following discussion. The categories are: structural methods, operational methods, economic methods and socio-political methods. Some methods can be implemented by the water utility, but others require action on the part of customers.

A structural method which can be undertaken by the utility is reduction of pressure in the water distribution system. This method is limited by the need for sufficiently high pressure for the purpose of fire protection. Flack (1982) expected that reuse of treated wastewater would increase as utility costs increased. Treated wastewater would be used more for irrigation or for recreational purposes, rather than as potable water. Structural methods which can be implemented by customers include the installation of water-saving plumbing fixtures and appliances and retrofitting of existing fixtures. Retrofitting consists of the installation of devices in existing plumbing fixtures which reduce the use of water. Toilet dams are an example. These restrict the volume of water used per flush to less than the normal contents of the tank. The installation of a household greywater recycle system is another structural method. Greywater is water which has been used only for washing. Greywater can be used again before it leaves the residence for applications which do not require high quality water. For example, it could be used for flushing toilets. Outdoor residential water use can be reduced by increasing the effectiveness of irrigation. Landscaping with plants which do not require so much water is another possibility.

An operational method of demand management is detection of leakage from the water distribution system and subsequent system repair. Customers can reduce their use of water through the detection and repair or replacement of leaking fixtures. In keeping with the integrated view of an urban water system of Figure 2.4, another category of leakage must be considered. This is leakage into the wastewater collection system (Robinson et al., 1984), known as inflow and infiltration. Inflow occurs during precipitation events and consists of surface runoff. Infiltration is seepage from groundwater into sewers. Infiltration is only influenced to a certain degree by precipitation events. Reduction of inflow and infiltration is important in managing the demand for wastewater treatment. Another operational method which is implemented by the utility is the imposition of restrictions on particular uses of water. Restrictions on water use for landscaping are particularly common.

Economic methods of demand reduction can be implemented by water utilities. These include pricing mechanisms, incentives and penalties. A prerequisite for the use of pricing in demand management is metering. Pricing needs to be given more attention than other mechanisms for implementing demand management because of the focus of Chapters 6 and 7. This issue is dealt with in more detail in Subsection 2.6.3.

An important socio-political method of demand management is public education. This provides information about what can be done to reduce water use and helps to establish a conservation ethic. Legal methods such as building code modifications also fall into this category. An example of the latter is the requirement in Ontario that only 6 L flush toilets be installed in new buildings. Another example is the prohibition of the use of water for once-through cooling in industries in the Regional Municipality of Waterloo. Socio-political methods mostly involve action by the utility or by government at the municipal or higher level. However, Robinson (1986) mentions public demand for demand management. This can be a factor in motivating utility or government action.

The various methods of demand management are interconnected in their effects. Pressure reduction in water mains may lead to reduction in water losses from the water distribution system. The implementation of structural and operational methods by customers is influenced by the availability of information about these methods. Technical change, such as the replacement of normal toilets by ultra low-flush toilets, will change the demand curve (see next subsection) of a customer (Brooks and Peters, 1988). Pricing methods support a conservation ethic and structural and operational changes by customers.

2.6.3 The Effect of Price on Demand for Water

The relationship between price and demand can be represented as a demand curve, in which quantity demanded is plotted against price. Often the relationship is summarized by the price elasticity of demand, defined by:

$$e \equiv \frac{dq/q}{dp/p} = \frac{d\log(q)}{d\log(p)} \qquad \text{eq. 6.1}$$

where e is elasticity, q is quantity demanded and p is price. In cases where explanatory variables other than price also enter into the demand curve, the partial differential of log(q) with respect to log(p) substitutes for the full differential. This method of summarizing implicitly assumes that elasticity is constant, giving a functional form of:

$$q = ap^{e} \qquad \text{eq. 6.2}$$

where a is a constant. Constant elasticity is frequently justified empirically. However, it is more general to consider elasticity as a function of price. MacNeill and Tate (1991) recommended using the constant elasticity form when information is too limited for a full econometric model. A report for the California Urban Water Conservation Council (Mitchell et al., 1994) gave only data on elasticity in a discussion of the response of water demand to price. Hanke (1978) suggested using equation 6.2. However, Hanke and de Maré (1984) reported a case where a linear relationship between quantity demanded and price was more appropriate. Howe and Linaweaver (1967) found residential indoor demand to be best characterized by a linear function, but outdoor sprinkling demand to be better represented by a multiplicative (constant elasticity) function.

Pricing has been used in water demand management (Billings and Day, 1989; Cuthbert, 1989). Price is a variable which affects the intensity and the extent of water use.

Water is used for various purposes which can be called end uses. Price affects the extent to which water is used for a particular end use and how efficiently water is used for that end use. If price increases a customer may decide that his lawn doesn't really need as much water as before, or that it might be time to invest in a water efficient toilet. A water intensive industry looking at locating in a city with a high water price might decide against such a move, or it might relocate only if it could reduce its dependence on water by becoming more water efficient. A number of studies have indicated that water demand is responsive to price, for example Howe and Linaweaver (1967) and Grima (1972). A review of literature on price elasticities for municipal water can be found in Prasifka (1988).

Table 2.2 Ranges of Price Elasticity of Demand for Water

	Short-run	Long-run
Residential		
winter	n.a.	0.0 to -0.1
summer	n.a.	-0.5 to -0.6
sprinkling	n.a.	-0.7 to -1.6
combined	0.0 to -0.30	-0.2 to -0.4
Industrial		
aggregate	n.a.	-0.5 to -0.8
by industrial category	n.a.	-0.3 to -6.7
Commercial		
by commerical category	n.a.	-0.2 to -1.4

The issue of time scale when evaluating price elasticities is an important one. Watt (1995) mentions for example the failure of many models of national or international economic processes to take into account the length of time taken to change infrastructure in response to changes in energy price. Ranges of price elasticity for water were reported by Boland et al. (1984). These are given in Table 2.2. Short-run means one year or less, and long-run means at least several years. Note that the range for summer water demand refers to the eastern US, i.e. the humid climate half of the US. Note the great range of elasticity by industrial category. An implication of this is that as price increases, the proportion of industrial water demand should decrease. This effect may be an important outcome of demand management by means of higher prices. Reduction in the ratio of industrial to total water demand could result from a selection against those industrial activities which are more water intensive. Another possibility is that there is selection for increasing water use efficiency without excluding particular industrial uses. It is more reasonable that there is a contribution from both these mechanisms.

Producing water is a capital intensive operation. There must be supply capacity in place to meet expected demands. It is forecast peaks in demand which such capacity is designed to meet. Seasonal peaks are by far the most important; daily and weekly peaks are generally small in comparison to the summer seasonal peak. In non-peak periods, part of the supply capacity remains idle. We are accustomed to the situation where cities continue to grow in population. Frequently the response is to increment supply capacity in rather large steps. When a new 'step' has been completed, capacity will exceed even peak demands for some period of years. There are thus periods soon after a 'step' when capacity is unconstrained. As demand grows, capacity becomes more and more constrained until there is a decision to add another 'step' increment to the supply capacity. Demand management may or may not have been integrated into this step-wise growth of capacity.

The utility, of course, incurs costs in these processes. Various sources of revenue are used to cover these costs: water rates, property taxes, connection charges, and grants and subsidies from higher (provincial or federal) levels of government (Ontario Municipal Water Association / American Water Works Association, 1979). Water rates are volume-based prices for water. A connection charge is a fixed charge, i.e. independent of the amount of water used, per billing period. Revenue may also come from development charges. A development charge is a charge levied at the time of connection of a new building to the municipal water system. Loudon (1984) reported that development charges were accepted by the Ontario Municipal Board as a legitimate means of raising revenue for capital expansion.

With volume-based water rates, the price of water depends on the quantity consumed. Different relationships between price and quantity consumed are set by the providers of water and wastewater services. These different relationships are called price structures or rate structures. Three common price structures are shown in Figure 2.5: uniform rate, declining block, and increasing block. Fixed connection charges per billing period are often used in conjunction with the various water rate structures. In what is known as a flat rate structure, there is only a fixed charge per billing period, with no price set per volume of water used.

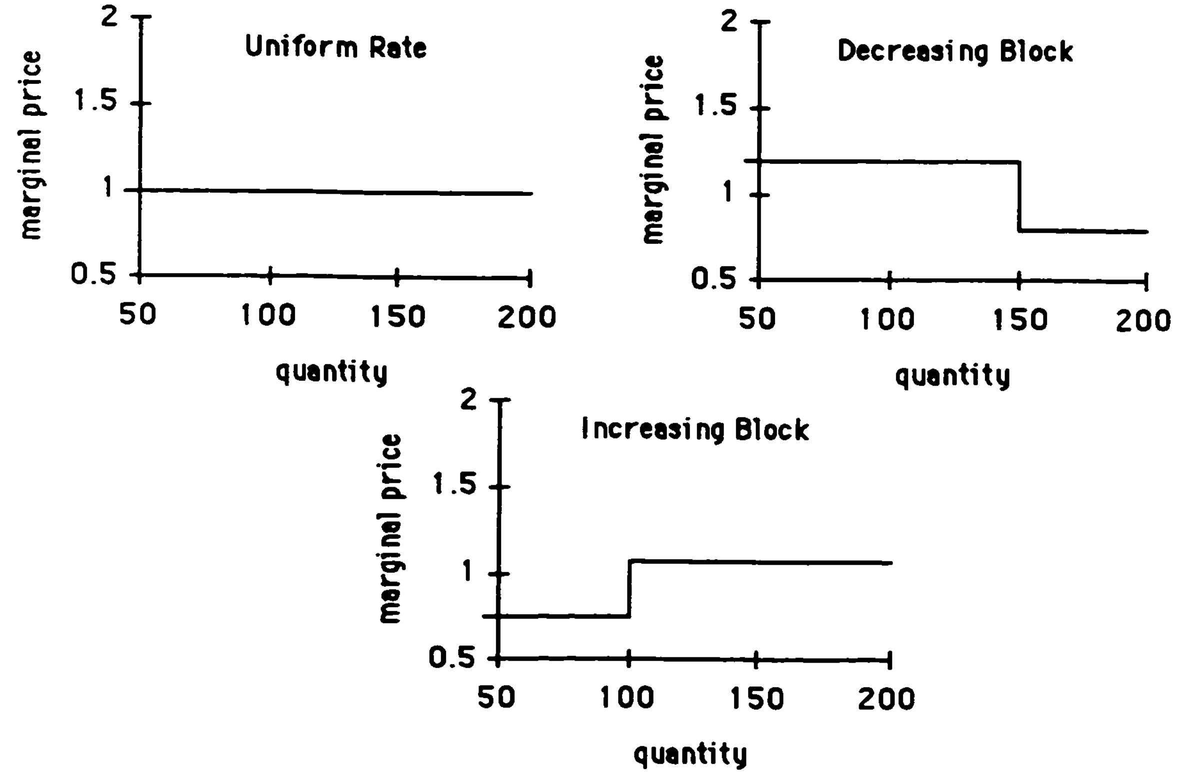

Figure 2.5. Marginal price as a function of quantity consumed for different price structures: uniform rate, decreasing block and increasing block.

Marginal price is the price faced by the customer for an additional unit of water. Given the connection between water demand and price, the various price structures have quite different demand management potential. Flat rate structures provide no incentive to conserve water, since the marginal price is zero, while at the other extreme, increasing block rates provide considerable incentive to keep water use below a certain level. Of course, in addition to price structure, the price levels play a role providing incentive to reduce demand.

One way of classifying these costs is either as variable or fixed costs. Variable costs are those associated with the quantity of water produced. These costs are associated with such things as chemicals for water treatment, and electricity for pumping. Fixed costs are those which have to be paid regardless of the quantity of water produced. Capital costs are typical fixed costs, since in-place capital cannot be easily changed with respect to variations in quantity of water produced. However, capital costs representing normal maintenance and replacement activities can be considered variable costs.

A second distinction with respect to costs which can be made is between marginal costs and average costs. Total cost to the utility in a budget period is a function of the quantity of water produced. Marginal cost (per unit) is the cost of producing an additional unit of water. Therefore the marginal cost is the slope of the total cost curve. The average cost (per unit), at any point on the total cost function, is the total cost divided by the total quantity of the water produced. So long as producing an additional unit of water does not require additional supply capacity, marginal cost can be approximated by the variable cost of producing the unit of water[1]. In this situation, marginal cost will be less than average cost.

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[1] In New South Wales, were a form of marginal cost pricing has been adopted, variable cost is used to represent marginal cost, in situations when capacity is not constrained (Government Pricing Tribunal of New South Wales, 1993).

Municipalities who charge a uniform rate for water have in general favoured setting the price of water to its average cost. This is because if water sales can be reasonably predicted, an average cost price will generate the required revenue to cover costs. On the other hand, economic theory favours marginal cost pricing (Hanke, 1978; MacNeill and Tate, 1991; Mitchell et al., 1994). This means setting the marginal price of water to the marginal cost of water. Marginal cost pricing is based on 'economic equilibrium' (see Section 2.3). As such, it is intended to maximize net benefits under the prevailing market conditions. A practical implication of marginal cost pricing is that total revenue is unlikely to equal total cost. In the situation where average cost is greater than marginal cost, a solution to this problem is to charge a fixed amount per billing period in addition to the per volume water rate.

Marginal costs can be calculated over a longer time period which may include a capital expansion. In this situation, the longer term marginal cost likely will be greater than average cost, even though the short term marginal cost is still less than average cost. It is summer peak demand which drives the need for expansion, and so it has been argued that those who contribute most to the summer peak should pay more for their water. This is the main rationale behind a price structure which can be called a summer use charge (see Chapter 7). This is like an individualized increasing block structure (Figure 2.5), where the quantity at which the switch is made to the upper block is related to the individual customer's winter water use level. This justification of a summer use charge is based on equity, not economics. According to traditional economic theory, the way to reduce summer peak demand is to charge a uniform summer rate higher than the uniform off-peak rate. The increase in the summer rate with respect to the off-peak rate is determined by the long run marginal cost of capacity expansion (MacNeill and Tate, 1991; Mitchell et al., 1994).

According to environmental economics, marginal costs should be adjusted to account for environmental costs and benefits not borne directly by the utility (Jordan, 1995). Such costs are external to the circulation of goods and services in an economic system. There may therefore be considerable difficulty in quantitatively establishing what the external costs and benefits are (Gowdy and O'Hara, 1995).

3

Development and Sustainability

In this chapter, a description of development is presented based on complex system theory. Ecosystems and economic systems are both self-organizing systems far from thermodynamic equilibrium which maintain their structures by dissipating high quality energy. The requirements of thermodynamics and of adaptability in an uncertain environment lead to a pattern of increasing specialization and efficiency of subsystems whether in an ecosystem or an economic system. However, the same thermodynamic and adaptability theoretic influences eventually bring about instability. Development, as defined in this chapter, is therefore unsustainable.

Ecosystems containing humans are not exempt from the cycle leading from development through crisis to rejuvenation. It can be assumed, or decided, that only humans design. Therefore development by design can only occur in ecosystems containing humans. Such ecosystems contain a natural, i.e. non-human, sector and an economic sector, or economic system. However, the distinction between development by self-organization and development by design is not clear-cut. This is because ecosystems containing humans are reflexive (Funtowicz and Ravetz, 1994) with the designers being integral parts of the designed systems. The design activities of humans cannot in principle be separated from other self-organizing processes. Development by design may change the form of a developed economy and may lessen the impact of eventual crisis. However the overall conclusion is still that development, as defined here, is not sustainable. This is a general conclusion which is not based on arguments about the particular historical situation of the current world economy. It applies equally well to economic systems using only solar based sources of energy.

Some of the material in this chapter was presented in Creese (1996) or can be found in Creese et al. (1997).

3.1 Development as Self-Organization

This section describes development in self-organizing systems, without considering explicitly the role of design. It therefore describes development by self-organization. Several modes of economic development are then outlined.

3.1.1 The Dynamics of Development

Development was the first general trend in ecosystem dynamics noticed by ecologists. Ecosystems development is also called succession. It was introduced by that name in Section 2.3, where it was described as a process leading to ecological equilibrium and material balance between the living and non-living components of the ecosystem. The main features of succession were summarized by Odum (1969), who also used the term development to refer to succession. Consider a habitat, exploitable by life forms, but largely empty of them. The species which arrive early to such a habitat tend to be fast growing organisms which quickly build up populations. This is the beginning of succession. Later on these opportunists are out-competed by more efficient, slower growing species. During succession, there is an increase in efficiency-enhancing specialization (i.e. the number of species increases), and the total biomass of organisms increases. Also nutrient cycling becomes tighter, which is to say that there is less material transport across the ecosystem boundary. Since the ecosystem boundary is often an arbitrary human construct, tighter cycling implies that nutrients tend to remain bound up in living biomass, and that the residence time of unbound nutrients in the abiotic part of the ecosystem is short.

Development in economies evidently follows a path which is similar in many respects to ecosystem development: an increase in efficiency-enhancing division of labour, the accumulation of societal capital, and increased organization and connectedness. However, it seems that cycling does not become tighter, leading to problems of material balance: resource depletion and pollution.

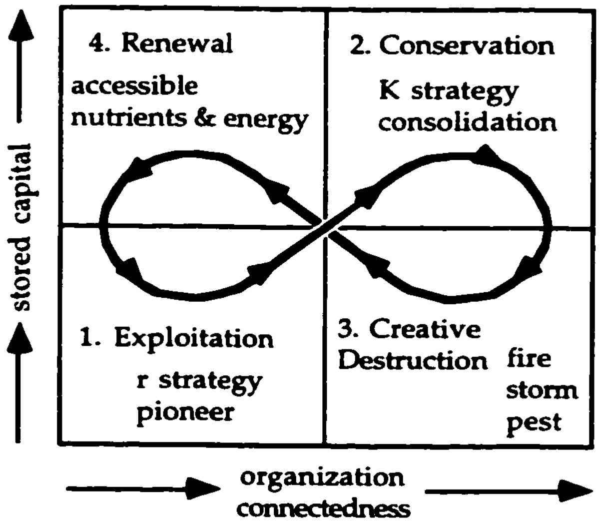

Figure 3.1. Holling's figure ∞ of ecosystem dynamics. Development, or succession, is the path from exploitation phase (1) to conservation phase (2).

After examining succession, ecologists had to recognize other types of ecosystem dynamics. Holling (1986) first proposed a 'figure 8' cycling through four dynamic phases. Figure 3.1 shows the four phases, exploitation, conservation, creative destruction (or release), and renewal, in a state space of organization or connectedness and stored capital. Kay et al. (1999) produced a version of this diagram in which the 'organization and connectedness' variable was replace by an 'utilization of available energy' variable, and the 'stored capital' variable was replaced by a 'stored available energy' variable. In a natural ecosystem, the available energy utilized generally comes from sunlight, and storage of available energy is in the form of biomass. In succession, the ecosystem moves from exploitation phase to conservation phase. As the ecosystem develops, its total biomass increases, and the interactions among components become more strongly linked due to competition and specialization. The strong linkage regime is brittle under the impact of perturbation, so that eventually a sudden reversal of the successional process ensues. Forest fires and pest outbreaks are examples. This is the transition from conservation phase to creative destruction phase in Figure 3.1. In the renewal phase, the bound materials of the biomass are converted to re-usable forms (nutrients), permitting the cycle to begin again. If the cycle is to begin again, information is needed to re-invent the ecosystem. The information must be provided by the presence of appropriate species of colonizing organisms, in the same way that a seed provides the information to convert minerals, carbon dioxide and water into a plant. How the ecosystem is re-invented will depend on what information is available.

The situation is actually more complicated than this due to the hierarchical, spatial, and temporal relationships among system components. Cycles of development, maturation, crisis, and rejuvenation take place quickly on a small spatial scale, and more slowly on a large spatial scale. With certain self-organizing components of ecosystems, these ideas are very familiar. Young animals and plants grow, mature and eventually die. The cells within them do the same, only faster. The biochemical processes of the cells run at an even faster pace. The same sort of cycle at the level of whole ecosystems is not as obvious because it is much less deterministic. One of the main contributions of current ecological theory is in explaining how the set of fairly independent organisms which inhabit an ecosystem can be caught up in a synchronizing process which leads to crisis for the entire ecosystem.

It is recognized in ecology that genetic evolution is another development process, which takes place in the context of succession-and-crisis cycles, even though the term development commonly refers to just the process of succession. Faber and Proops (1994) describe what they call ‘evolution’ in ecological and economic systems. Their terminology of is unusual, but instructive. They categorize evolution as genotypic or phenotypic. Genotypic evolution involves the production of new potentialities, which they also refer to as novelty. Phenotypic evolution, on the other hand, involves the realization, or working out, of potentialities already present. Pheonotypic evolution is predictable in principle, although it may not be in practice. Genotypic evolution is not predictable even in principle. It is evident from their discussion that phenotypic evolution in ecosystems corresponds to ecological development, or succession, in the usual terminology. Genotypic evolution in ecosystems corresponds to genetic, or Darwinian, evolution in organisms. According to Faber and Proops, genotypic evolution in economic systems corresponds to change in the preference orderings of economic agents, technological innovation, and change in legal, economic and social institutions. The end point of phenotypic evolution in an economic system without novelty would be the general equilibrium of neoclassical economics.

Their qualification on the in-principle predictability of phenotypic evolution is due to the possibility of chaotic behaviour. Chaos theory has shown that there are deterministic systems which are predictable in principle but are unpredictable in practice (Gleick, 1988). These systems are deterministic in the sense that their operating rules are completely specified. Nevertheless, such systems can be so sensitive to initial conditions that their behaviour cannot be distinguished by statistical tests from random behaviour. Another characteristic of chaotic systems is bifurcation. This can occur when a deterministic system is sensitive to small changes in a parameter. As the parameter is changed smoothly, the system response curve is also smooth until some threshold value of the parameter is reached. Then, there is a sudden shift in behaviour. Beyond the threshold point, there are two possible equilibria for the system, only one of which is realized. Which one is realized appears to be random. A system may have several bifurcation points, and therefore many potential equilibria.[1]

3.1.2 Thermodynamics of Development

Thermodynamic principles determine the bounds with which real world processes operate. General directions of change in systems may be indicated by thermodynamics, but detailed mechanisms of processes are not specified. The first law and the second law are fundamental principles of thermodynamics which are generally recognized. This is still true even though the two laws were unified into a single statement independently by Hatsopoulos and Keenan (1965) and by Kestin (1966).

The first law of thermodynamics states that energy is neither created nor destroyed. For a system open to matter and energy flows, such as an ecosystem or an economy, this means that the sum of energy inputs and outputs must equal the net change in stored energy within the system. The first law aspect acknowledges interconversion of energy types such as heat, work, sunlight or other radiation, and chemical energy. The second law aspect of the unified principal places limitations of these interconversions

The second law requires that when any process takes place in an isolated system, the overall quality of energy in the system must be degraded. Isolated systems are those which have no exchange of energy or matter with their environments. A consequence of the second law is that gradients such as temperature gradients, chemical concentration gradients, or pressure gradients do not spontaneously appear in isolated systems.

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[1] Deterministic economic models illustrating bifurcation points have been constructed by Arthur (1989). He used these models to try to explain how the choice between certain production techniques was locked-in by historic events, in apparent disregard for which of the techniques was more economically efficient in the long-run.

Structures do not spontaneously appear in isolated systems. The property called entropy, serves as a measure of symmetry or lack of gradients. In isolated systems, entropy increases to a maximum, at which point all gradients are eliminated. The resultant state is referred to as a state of thermodynamic equilibrium. The universe as a whole is an isolated system, and since gradients still exist in the universe, its entropy is constantly increasing.

In everyday experience there are many systems which seem to be able to maintain themselves far from thermodynamic equilibrium. They exhibit gradients at their boundaries and also internally. A living organism has a chemical composition radically different from that of its environment. This can be stated in another way. It maintains a chemical gradient between itself and its environment. Ecosystems and economic systems also maintain gradients. The pattern of land settlement which we see as cities and rural areas is a form of gradient. Such systems are far from thermodynamic equilibrium.

The physicist, Erwin Schrödinger, examined this issue of how living systems seem to be able to contradict the second law of thermodynamics (Schrödinger, 1944). He concluded that organisms destroy entropy, i.e. create order, in the process of internal self-organization, but that in doing so, they create even more entropy in their surroundings. The net entropy change from the process of self-organization is therefore positive. In this way the entropy of the universe continues to increase despite the existence of self-organization systems. Such self-organizing system must be open to flows of matter and energy.

Georgescu-Roegen (1971) applied Schrödinger's principle to economic systems. Economic systems take high grade energy and convert it to unusable heat. They also take geological concentrations of mineral deposits (gradients) and disperse them. Economic systems must not only have sources of high grade energy and / or materials, they must also have a sink for the products of dissipation.

The unified principle of thermodynamics is stated in a manner most obviously applicable to isolated systems as they approach thermodynamic equilibrium, but Schneider and Kay (1994a) have given a restatement of the second law aspect of unified principle thermodynamics in a way suitable for its application to the non-equilibrium thermodynamics of open systems.

The thermodynamic principle which governs the behaviour of systems is that, as they are moved away from equilibrium, they will utilize all avenues available to counter the applied gradients. As the applied gradients increase, so does the system's ability to oppose further movement from equilibrium.

Not only must the net amount of entropy which a self-organizing system produces be positive, as Schrödinger postulated, the net amount of entropy produced must be greater than the net amount of entropy which would be produced if the system did not exist. In other words, the more organized a system is (the farther from equilibrium), the more entropy it must produce in its environment. This is what is required for it to maintain its internal organization. As system which does this is a dissipative, self-organizing system. The self-organization by dissipative systems results in the formation of new structures, which are also new gradients. Even though 'nature abhors a gradient' (Schneider and Kay, 1989), the new gradients can build up within a system so long as the overall gradient destruction of the system plus its environment is greater than it would be without the existence of the dissipative system.

Schneider and Kay (1994b) related these thermodynamic ideas to development in ecosystems. They hypothesized that a more developed ecosystem must have a higher gradient destruction rate than an immature ecosystem. They then demonstrated empirically that this is the case. In the course of succession[1] more and more of the available energy of the solar radiation input to a natural ecosystem is degraded. A related idea is that tropical

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[1] The process of development of ecosystems is more often called 'succession' by ecologists.

ecosystems can reach a more developed condition than temperate ecosystems, because they have more solar radiation available to degrade.

The implication for economic systems is that the level of development (by self-organization) is linked to the rate of degradation of high grade energy by the economic system. Prior to this conclusion based on thermodynamics, a number of authors had already theorized that social and economic development is related in a similar way to energy utilization (see the review by Rosa and Machlis, 1983). How far an ecosystem or an economic system can progress in development depends on its ability to destroy gradients. What is different about modern industrialized societies, as compared to earlier societies, is the importance of dissipation of high quality energy other than solar energy. By increasing the quantity of high quality energy which is degraded, modern industrial economies have reached a state of development which is not attainable by economies based only on solar energy.

As set out at the beginning of this subsection, thermodynamics identifies general directions and conditions for real world processes to follow. It does not, however, concern itself with the details of processes. The role of price in the theory of economic development expounded by Barnett and Morse (1963), for example, is mostly not in conflict with the theory of development presented here. As a resource becomes scarcer, its price increases, inducing its replacement by some other resource, inducing technological change to adapt to the scarcity, or inducing the discover of new sources of the resource. As might be expected by the thermodynamic interpretation of development, these economic processes induced by price change have in general served to increase the degradation rate of high quality resources, especially energy. For example, as copper has become scarcer, aluminum has replaced it in some applications. Some 20 kWh per kg of available energy is required to produce copper, while the corresponding figure for aluminum is 70 kWh per kg

(Chapman, 1973).[1] The exploitation of lower grade ores after high grade deposits have been exhausted results in increased degradation of high grade energy, which must be used to concentrate the lower grade ore. This is where the role of price suggested by Barnett and Morse (1973) breaks down. It requires energy for technology to accomplish economically valuable tasks and it also requires energy to do the research and development required to provide new technology. The overall effect of increasing resource prices fits neatly into the expected pattern of the development of a dissipative system.

Different dissipative processes have different rules or laws by which their behaviour is governed. Often these laws are not general, but are particular to given processes subject to given conditions. Conditions include thermodynamic conditions, dealt with in this subsection, but are not limited to these. Dissipative structures usually exist in an environment of other dissipative structures. Questions about how laws or behavioural descriptions of particular dissipative structures are affected by other dissipative structures in their environments are dealt with by adaptability theory.

3.1.3 Adaptability Theory

Adaptability is the ability of an adaptive system, such as the biota of an ecosystem, to survive in spite of uncertainty in its environment (Conrad, 1983). In adaptability theory, environmental uncertainty and adaptability both take on formal definitions as information theoretic entropies. For continued survival, the adaptability of the system must be greater than the uncertainty of its environment. The fundamental inequality of adaptability theory is:

$$\textit{adaptability} \geq \textit{environmental uncertainty} \qquad \text{eq. 3.1}$$

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[1] These values per kilogram are not quite fair unless we know that 1 kg of aluminum can replace exactly 1 kg of copper.

The basic idea is that survival requires that the system must have a range of behaviours available to respond to changes in its environment. The potential uncertainty of the dynamic behaviour of the system must be at least as great as the uncertainty of its environment, with two important exceptions. The first is that it can be reduced by the ability to anticipate environmental change. The second is that the system can avoid certain regions of its environment, in effect contracting the uncertainty it faces by shrinking the part of the environment with which it interacts. Conrad called this second exception *indifference.* The fundamental inequality expands to the following:

$$\begin{array}{l}\textit{behavioural}\\ \textit{uncertainty}\end{array} - \begin{array}{l}\textit{inability to}\\ \textit{anticipate}\end{array} + \textit{indifference} \geq \begin{array}{l}\textit{environmnetal}\\ \textit{uncertainty}\end{array} \qquad \text{eq. } 3.2$$ [1]

When anticipation is at its maximum, the term 'inability to anticipate' goes to zero and all behavioural uncertainty is correlated to events in the environment. At minimum anticipation, the term 'inability to anticipate' is equal to the behavioural uncertainty term. But in this case, indifference provides the only adaptability, which is impossible since the system cannot eliminate its interaction with its environment. There must therefore always be at least some anticipation.

Behavioural uncertainty, anticipation, and indifference are all components of adaptability. Each of the entropies in equation 2.2 can be expanded to account for the

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[1] Formally, this is: $H(\hat{\omega}) - H(\hat{\omega} \mid \hat{\omega}^*) + H(\hat{\omega}^* \mid \hat{\omega}) \geq H(\omega^*)$. In general $H(\omega)$, called an uncertainty by Conrad (1983), is the information theoretic entropy of a transition scheme. A transition scheme is the set, ω, of probabilities of state-to-state transitions. A transition scheme, ω, is of the biota of the ecosystem, unless marked with an asterisk, *, in which case it is of the environment of the biota, i.e. the abiotic component of the ecosystem. Transition schemes marked with a hat, ^, are potential, which is to say that they relate to the most uncertain environment in which the biota could survive. Therefore $H(\hat{\omega})$ is the potential uncertainty of the biota, $H(\hat{\omega} \mid \hat{\omega}^*)$ is the potential uncertainty of the biota given $\hat{\omega}^*$, $H(\hat{\omega}^* \mid \hat{\omega})$ is the potential uncertainty of the environment given $\hat{\omega}$, and $H(\omega^*)$ is the actual uncertainty of the environment.

compartmental structure of a hierarchical system. When this is done, terms appear which relate to the interdependence of compartments. Each of the compartments can be thought of as having its own adaptability. Conrad showed that the adaptability of the whole system increases with increasing independence of the behavioural uncertainties of hierarchical levels and of compartments within levels. On the other hand, the adaptability of the whole system is increased by greater interdependence in anticipation among levels and compartments.

All of the terms on the left hand side of the inequality, including the interdependence terms, represent potentials which require the dissipation of available energy to maintain. One type of uncertainty in dynamic behaviour is the uncertainty of population size in an uncertain environment. Downward adjustment requires relinquishing stored available energy, while upward adjustment requires acquisition and utilization of available energy for growth and maintenance. In human societies, anticipating environmental change is aided by monitoring the environment, but physical (and financial) resources are used up in any monitoring program. A society which takes a long view and decides to reduce its carbon dioxide emissions is increasing its indifference with respect to the fossil fuel component of its environment. In the short run this might be accomplished by increasing efficiency, but in the somewhat longer term, if other societies do not do the same, the society will lose competitive advantage.

Because of the costs associated with adaptability, there is a tendency for ecosystem adaptability to be reduced in order to gain thermodynamic efficiency. The inequality of equations 2.1 and 2.2 thus tends to become an equality as the system trades off adaptability to gain efficiency. Given this tendency, it follows that there is also a tendency towards compensation among the adaptabilities of subsystems, a tendency which is more pronounced as the difference between system adaptability and environmental uncertainty decreases. This is what Conrad (1983) called the principle of compensation:

Changes in the adaptability of one level or unit of organization tend to be compensated by opposite changes in the adaptability of some other level or unit.

It also follows that when environmental uncertainty changes, it tends to be tracked by corresponding changes in system adaptability.

As competition increases in the course of development, the increasing connectedness requires greater dissipation of available energy to maintain a given level of adaptability. This is because it becomes increasingly less possible for a highly connected system to withstand internal change without damage. As development proceeds, and adaptability is traded off to gain competitive efficiency, the point is eventually reached where the system's adaptability is equal to the environmental uncertainty. At this point, an out-of-range fluctuation of the environment will cause a crisis in the system (from box 2 to box 3 in Figure 3.1). This could be called 'development to instability,' after Conrad's phrase 'succession to instability,' which he applied to ecosystems and economic systems alike. How far an ecosystem or an economic system will advance in development is dependent on the uncertainty of its environment, not only on its ability to destroy gradients.

3.1.4 Economic Development Modes

Historically, economic systems utilized the same solar radiation that ecosystems use. However, other sources of energy have become available with the advance of science and technology in modern society. Conrad (1983) outlined some ideas on economic development from an adaptability theoretic viewpoint. He considered that there were three basic modes of economic development, which can be called specialization, isolation, and failure. A fundamental idea in this classification is that the economy is there to provide goods, services, and creative opportunities to satisfy criteria established by the society. Here then design goals enter the picture. Using the adaptability theory framework, it would be hard to avoid setting a design goal. Ecosystems and their components are typically quite plastic. They transform in response to external and internal perturbations. It is therefore necessary to define system characteristics beyond which the system is transformed into a different system. Otherwise success or failure of adaptability would be meaningless.

The simplest of the modes of economic development is the failure mode. In this mode, the economy fails to provide the goods, services, and creative opportunities which the society wants. Since it is the economy which is under discussion, not the human society as a whole, society may still be in a position to sustain itself. According to the principle of compensation, it will have to do so by means of non-economic adaptabilities. Population adjustments due to disease, famine, or emigration are examples of non-economic adaptabilities. Physiological changes are also possible; several centuries ago Europeans were shorter than they are today.

In the specialization mode, economic development proceeds much in the same manner as in classic ecosystem succession. The characteristic feature is the presence of efficiency-increasing specializations and greater complexity. The cost of adaptability for individuals increases to the point where it becomes more efficient to provide adaptability at the societal level, so new levels of social organization arise. Due to the increase in complexity, there is a decrease in stability, and also a higher cost to maintain stability. If the society is in contact with other societies, not just internal specialization, but also external specialization increases, with the result that environmental uncertainty increases. This implies a need for increased adaptability. Compensating societal 'organs of instability' are created to provide this, such as research institutions.

The isolation mode of economic development is characterized by the attempt to limit the requirement for adaptability through the indifference component of adaptability. A boundary is maintained between the society and other societies. This reduces environmental uncertainty and permits the society to be externally unspecialized. Because of the lack of external specialization, the society as a whole is not as efficient as it would otherwise be. There is therefore less high quality energy available and internal specialization is consequently less developed. The economy is at risk if its wall of indifference is breached by another more specialized economy.

Conrad does not seem to have considered the question of whether the specialization mode of development will inevitably lead to specialized failure of some of its parts. By this I mean specialization into rich and poor, the creation of a wealth gradient. This could also be viewed as an economy in specialization mode occupying the same geographic space as one in failure mode. And similarly, when an economy in specialization mode is geographically separate from an economy in failure mode, but there is a trading relationship between the two economies, it seems reasonable to view both economies as part of the same specialized system.

3.2 Sustainable Development

In Section 3.1 a theory of development was described. The intent of that section was to show that economic development, or at least the economic development of this theory, is not sustainable. This is important because, whatever other ideas or definitions of economic development there may be, the theory of Section 3.1 represents real constraints which any other definition of development must take into account.

It seems to me that there are two major obstacles to sustainable development. The most obvious obstacle is the problem of material balance. Closely related to this is the idea that a given level of development can be maintained only by a suitable rate of energy degradation. The material balance cannot be maintained without the energy required to keep the material flows going. The other obstacle is that development leads to instability. Pollution and resource depletion can be viewed as issues of material balance. The environment of an economy is materially changed in ways detrimental to the continued development of the economy. Balance is most particularly a modern difficulty because of the much greater size of our economic systems than heretofore.

The issue of material balance is often addressed in terms of carrying capacity. Carrying capacity denotes the maximum population of a particular species which can be supported by a particular environment for an indefinitely long time period. Carrying capacity is most easily expressed in terms of some limiting resource present in the environment of the species in question, with the assumption that this resource is renewable. If the population is below the carrying capacity, the population grows. This consumes some of the resource, so that there is less available for more population growth. The resource can be thought of a 'bound' and 'unbound'. As the population grows, more of the resource is bound up within the organisms, but due to death and catabolism, the resource is also constantly being regenerated, or unbound. When the population reaches the carrying capacity, binding and unbinding balance each other. The relationship of carrying capacity and resource availability with respect to a growing system is shown in the left-hand graph of Figure 3.2. It could be said that a developing system appropriates carrying capacity from its environment.

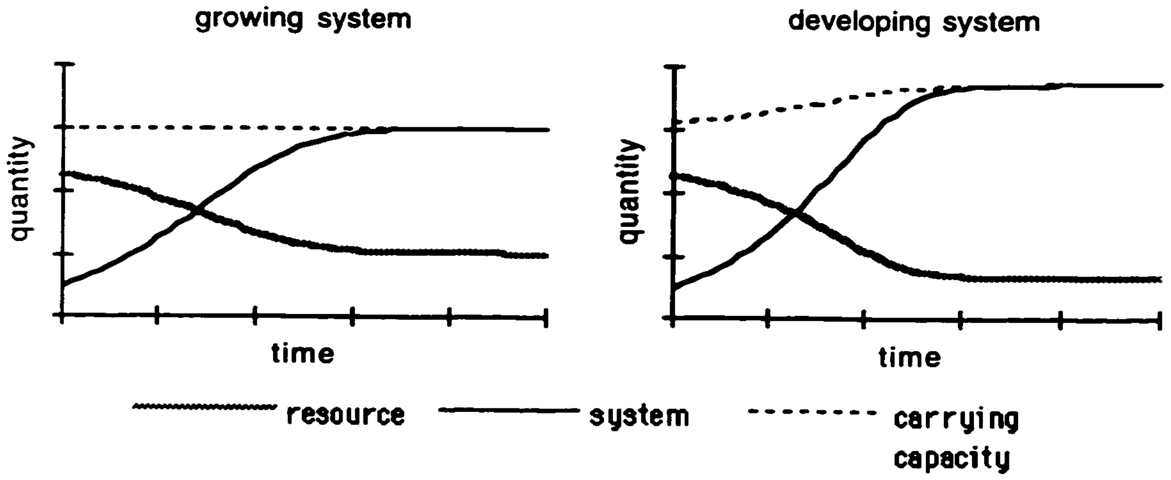

Figure 3.2. Carrying capacity and renewable resource availability for a growing system (constant efficiency) and for a developing system (increasing efficiency).

One of the features of self-organizing systems is that they are made up of subsystems which are to a greater or lesser extent in competition.[1] The subsystems are themselves self-organizing systems which 'try' to get as much of the system's resources as they can. Competition results in selection for efficiency. The more efficient subsystems proliferate. This permits the system as a whole to extract more resources from its environment. The carrying capacity actually changes. It is a function of the efficiency of the system. Thermodynamically, this is as it should be. If a particular resource represents a gradient that can be destroyed, then the resource is a source of high grade energy. If not, then there must be another resource being used which *is* a source of high grade energy. In either case, the more efficient the system components, the less high quality energy the whole system will degrade. This is not possible thermodynamically, so the system grows in size so that it degrades at least as much high quality energy as it would with lower efficiency components. No resources are actually freed by the increase in efficiency, except perhaps temporarily. In fact, all else being equal, more efficient self-organizing systems will grow to a greater size than less efficient systems. The growth of a developing system is shown in the right-hand diagram of Figure 3.2.

Energy utilization increases during development despite the increasing efficiency of system components that accompanies the developmental process. The idea that increased efficiency in an economic system would result in growth was first enunciated more than a hundred years ago by Jevons (1865). He took up the question of whether increasing the efficiency of burning coal would help extend coal reserves in nineteenth century Britain.

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[1] This is not true for self-organizing systems which are termed 'autopoietic'. Such self-organizing systems also have a pre-programmed maximum size, so that carrying capacity is not a useful concept for them. Individual biological organisms have this property. In contrast, economies and ecosystems do not have such 'programming'. They are examples of 'sympoietic' systems. The autopoietic/sympoietic distinction among self-organizing systems was introduced by Dempster (1995 and 1998).

His conclusion was it would do just the opposite because more uses for coal would be developed if efficiency were increased.

The second obstacle to sustainable development, the repeated oscillations between development and crisis, is not particularly a modern problem. In fact, due to a centuries long period of more or less continuous development, we in the developed world tend to be out of touch with this problem. Braudel (1981-1984) described the cycling of European population in the 15th-18th centuries. Economic growth stimulated population growth. When population expanded, marginal land was brought under cultivation. Eventually agricultural production proved limiting and famine or epidemic reduced population. After the population fell, living standards improved for those who were left. Put in terms of the principle of compensation of adaptabilities, when economic adaptability failed, it was compensated by human biological adaptability. When human biological adaptability went through a crisis, the marginal land went out of production and was recolonized by the natural sector of the ecosystem. The history of the last two centuries seems to indicate that we in the developed world have broken free of this. The previous section indicates that the escape is temporary.

What becomes of the idea of sustainable development? One way is simply to redefine sustainable development. In their book, Limits to Growth, Meadows et al. (1972) modelled the world economic system. In the standard run of their model, population, food production, and industrial production all grew and then declined sharply early in the twenty-first century. These variables eventually all stabilized at low levels. For Braat (1991), these results still represent sustainable development, because the human population did not go to zero. To me, this definition renders the term 'development' meaningless.

There is a sense, however, in which ecological succession has been sustainable, in spite of repeated crisis. Development has proceeded at the genetic level, with the evolution of more and more complicated life-forms. The economic analogy is that cultural, especially technological, information can survive and evolve through episodes of economic crisis.

This is important and should not be ignored, but I think it is not what people primarily want when they speak of economic development.

What people particularly want is to keep their own human biological adaptabilities well buffered by their economic adaptabilities. They do not want food production and human population to rise and afterwards fall precipitously. This inference leads to another view of development, which is that development pertains to how people want to live. From the adaptability theory point of view, one problem for an economy is to provide goods and services according to criteria established by society (Conrad, 1983). An adaptable economy is able to meet the established criteria. This is also essentially the view of Robinson et al. (1990) about sustainable development, that development pertains to the achievement of a set of societal goals about standards of living, and sustainable development is about trying to maintain those standards of living in the long run. A sustainable economy is an adaptable economy. In this view, sustainable development is a continuing struggle which can never be won once and for all; there will be set-backs. This view makes the concept of sustainable development appear utopian. This does not mean that it is a useless idea. Wallerstein (1991) viewed a utopia as "a process, always defining the better in a way critical of existing reality". The concept of sustainable development is useful in providing a focus for debate about the future. This view of sustainable development is consistent with the relationship between sustainability and development presented in Figure 1.1.

At the level of species in the hierarchical organization of ecosystems, different organisms exhibit different modes of adaptability. Very simple organisms, such as bacteria, adapt to their environment mainly by adjusting their populations up or down, and by the genetic evolution which such population change enables. These particular modes of adaptability are also available to more complicated organisms such as ourselves, but for us they are relatively more costly than they are for bacteria. The smaller role played by these modes of adaptability in humans implies that we have developed other modes of adaptability, in accordance with the principle of compensation. Conrad's view is that in order for an economy to cope with change in its natural and economic environment, it requires the evolutionary adaptability of creative thought, since creative thought provides a great potential for behavioural uncertainty. Conrad described a functional (chicken-and-egg) circle illustrating the relationship between goods and services and creative thought (Figure 3.3). He emphasized that much of creative thought is not monetarily measurable. In developed societies, that is in societies where high connectedness has reduced adaptability at the hierarchical level of individuals, compensating "organs of adaptability," such as research institutions and universities, have arisen at the societal level.

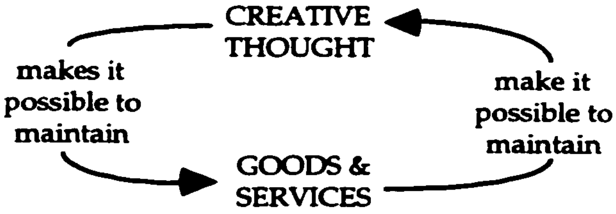

Figure 3.3. The functional circle of an economic system, with creative thought as the source of adaptability for economic evolution (adapted from Conrad, 1983).

The practical problems of sustainable development have global and local dimensions. Giampietro (1994) examined how the issue of scale relates to sustainable development from the perspective of hierarchy theory. Just as there are contradictions among goals at different time scales, so are there contradictions among goals at different spatial or organizational scales. Suppose we accept that economic activity is causing global climate change. International organizations have recognized that limiting carbon dioxide emissions is a useful response. At lower hierarchical levels, however, firms and individuals see things differently. For them, economic competition requires making the best use of available resources, including fossil fuels. The ideology of efficiency developed at lower hierarchical levels, can easily come to pervade a higher level, such as an individual nation.

In this situation, higher level adaptabilities can be deliberately reduced by design, resulting in a short-term gain in efficiency, and increasing the likelihood of development to instability. Conrad contended that the evolutionary tendency towards erosion of adaptability is generally accelerated in economies due to this process.

3.3 The Need for Adaptive Management

In spite of what was written in the previous section about the conflict between local and global goals, the principles of adaptability theory apply at both levels. The economist, Joseph Schumpeter (1943), noted that:

> *A system—any system, economic or other—that at every given point of time fully utilizes its possibilities to the best advantage may yet in the long run be inferior to a system that does so at no given point in time, because the latter's failure to do so may be a condition for the level or speed of long-run performance.*

How much emphasis a firm is able to give to adaptability depends on its business situation. Using the terminology of Figure 3.1, is its situation one of exploitation or conservation? Adaptabilities which it can afford in exploitation phase may have to be abandoned in conservation phase. By doing so, it will gain needed competitive efficiency in the short term, with the possible loss of long term viability. This applies to a business firm in the environment of other business firms, but just as well to an economy in the environment of other economies.

Economic entities are never the whole environment. There is also the natural environment. Suppose the biota of an ecosystem is divided into two components: the designers and the designed. Assume that the designers will want to make the designed subsystem more efficient as a source of economic goods and services. The first step is to produce a dynamic model of how the designed subsystem works and should work. Then constraints are introduced to the designed subsystem to make it more predictable, and to make it more predictable in an efficient way. The increased predictability results in a decrease in the behavioural uncertainty component of its adaptability. The increased efficiency and reduction in adaptability indicate that the designed subsystem has been moved to the conservation phase of Figure 3.1. It may be poised to move on to crisis.

A good example of this is the spruce budworm problem in eastern Canada studied by Holling (1978). The budworm control program, consisting of aerial insecticide spraying, interfered with the normal 'boom-and-bust' dynamics of the budworm-balsam fir interaction. The spraying program controlled budworm populations, but kept the system perpetually on the verge of a major budworm outbreak. To avoid this problem, Holling perceived the need for a different style of environmental management, which he labelled 'adaptive management'.

The key point is that the designers are still part of the system, a system which they are causing to lose adaptability through the imposition of the constraints needed for efficiency and predictability. According to the principle of compensation, the loss of adaptability in the designed subsystem must be compensated if the system is to be sustainable. If the compensation is not (by design) forthcoming from the designed subsystem, then the adaptability of the designers must increase. This will be true even if the designed subsystem includes a segment of society. The situation is the same as in cybernetics, where the variability of a controller must be great enough to buffer the dynamics of the controlled system. This is what Ashby (1956) called the "principle of requisite variety". To put the situation in Conrad's words:

> *...it is quite natural to extrapolate this paradigm of modeling, prediction, control, and design from local situations, where it is often successful, to global situations. We arrange these local situations in the most efficient way for some particular purpose and so the tendency is to think that it should be possible to do the same for the global situation. The*

usual thought is that the only difference is that optimization is harder for a big problem. Fortunately this is true, for the real problem is that a global system which is forced to be predictable is a badly thought out system. Design in these global cases should concern itself with the proper organization of potentiality, not with its suppression in order to obtain efficiency or predictability. - Conrad (1983)

Adaptability is needed to sustain societal goals. How much adaptability it is judged will be needed depends on how uncertain the future appears. Adaptability has a cost, the reduction of short term competitive efficiency. There is therefore a tendency to dispense with adaptability for the sake of efficiency. This tendency should be recognized. In a loosely connected (growing) economic system, maintaining adaptability is possible, but in this situation adaptability can be deliberately and unnecessarily thrown away due to an ideology of efficiency. In a highly connected (stagnant or shrinking) economic system, it is next to impossible to maintain adaptability without economic crisis of nations, firms, individuals or families. Such crises are in themselves a form of adaptability. Adaptability in the form of sudden demographic adjustments due to famine or epidemic, illustrate the compensation principle. Human biological adaptability compensates in these situations for loss of economic adaptability. Any design goals for development by design should consider which forms of adaptability are desirable and which are to be avoided. This is design of the 'proper organization of potentiality'.

When economic systems fail, their re-establishment depends on adaptability in the form of cultural information. Discussion about sustainable development should be in part about strategic choices of what kind of information is likely to be most useful. Which technologies are the most desirable to preserve as fossil fuel reserves are depleted? Should and can older, less energy-intensive technologies be revived?

Design and management with only local goals in mind does not support adaptabilities appropriate for sustainable development, because competition between local entities accelerates the trade-off of adaptability for efficiency. Only more inclusive goals can slow down the loss of adaptability. For example, reduction of carbon dioxide emissions seems to be a reasonable global goal, even though it is not now in the competitive interests of any nation taken alone.

The process of dynamic modelling, design, implementation, and management is an important mechanism of anticipation (in the adaptability theory sense) in modern society. This has been called 'anticipatory management' by Kay and Regier (2000) to distinguish it from the adaptive management of Holling (1978). According to adaptability theory, there are theoretical limits on the efficacy of this process. The theoretical limits are most keenly felt in a highly connected system. We are at present in such a situation with regard to the global impact of human societies on the natural sectors of ecosystems. The tendency is to want to expand the focus of the models, that is to attempt a more comprehensive, more integrated approach. What is probably more important in this situation is for the potential, of both the economic and the natural sectors of ecosystems, to respond to unexpected events to become a more valued component of design. Attending to the proper organization of potentiality is the basis for adaptive management.

3.4 Summary

Development is characterized by increasing structure, organization, and specialization, maintained thermodynamically by increasing the utilization of high quality energy. This kind of development is common to ecosystems and to the economic sectors of ecosystems. This is what I have called development by self-organization. It is not possible to sustain.[1]

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[1] "This impossibility of a macrosystem not in a state of chaos to be perpetually durable may one day be explicitly recognized by a new thermodynamic law just as the impossibility of perpetual motion once was." - Georgescu-Roegen (1975).

A second view of development is presented which is prescriptive rather than descriptive. Development is redefined as the achievement of societal goals about standards of living. This is development by design. Sustainable development is about continuing to meet the goals in the long term. The idea is viewed as utopian, but nevertheless as a useful focus for discussion.

Development by design might at first seem to offer a way make development sustainable. In this sort of development, criteria of desirable features of society and the natural environment are established by some sort of social agreement. If monolithic social agreement were attainable, development by design would eventually reach a crisis phase, just as development by self-organization does. The only difference would be that it would reach crisis phase with different constraints.

Adaptability is required to sustain desirable societal characteristics. This always has a cost in terms of reduced short run competitive efficiency. According to adaptability theory, an important element of the design of development should be the potential to respond to an uncertain environment, but that this can only be done by relinquishing some predictability and efficiency. This is the essence of adaptive management. This is equivalent to accepting numerous small crises instead of a few large ones. This situation would have to be included as a design feature of development by design. This seems to be an area where social agreement is least likely to be achieved.

4

Urban Water Systems and Sustainability

The purpose of this chapter is to look at urban water demand management from an ecosystem perspective in order to come to an understanding of how it (demand management) relates, or can relate, to the sustainability of a socio-economic system. In what follows, urban water demand management is taken as a possible element in the design of a sustainable society.

In social planning, 'development by design' meets 'development by self-organization'. Social planning was described by Simon (1981) as 'designing the evolving artifact'. Simon tried to make a clear distinction between the artificial, or man-made, and the natural. In planning for sustainability, the 'natural' ecological environment and the 'artificial' socio-economic system must both be considered. To the extent that design or management choices are made for the natural environment, the distinction between natural and artificial is blurred. As a way of referring to the combined socio-economic and natural system, I will use Conrad's phrase 'economic ecosystem'.[1] An economic ecosystem has all the properties of complex systems discussed in the previous chapter. Therefore, a complex systems approach is needed for discussing the behaviour of an economic ecosystem, including its sustainability.

The methodology in this chapter is based on a complex system approach. In part, the methodology is based on the idea of ecosystem integrity. The meaning of ecosystem integrity from a non-equilibrium thermodynamics viewpoint has been elaborated by Kay

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[1] "By an economic ecosystem I mean an ecosystem to which the special constraints of an economy are added." – Conrad (1983).

(1991). A methodology for the application of an ecosystem integrity to ecosystem management was proposed by Kay et al. (1999). Since a socio-economic system depends on its natural ecological environment, it should affect that environment only in ways which do not fundamentally change it, so that it in turn does not adversely affect the socio-economic system. Therefore, maintaining the integrity of an economic ecosystem has been equated with the sustainability of the economic ecosystem by Kay and Regier (2000).

In this chapter, the notion of the integrity of an economic ecosystem is combined with the ideas of balance and adaptability[1] to the problem of the design of sustainability of an economic ecosystem. The effect of including urban water demand management on the sustainability of an economic ecosystem is evaluated.

4.1 Methodology

This section is devoted to the elaboration of a methodology for the design of sustainability, based on the methodology of Kay and Regier (2000), but with modifications based on adaptability theory. Their methodology is fundamentally an ecosystem approach. Socio-economic systems are considered to be embedded within ecosystems. The phrase 'an ecosystem approach' has become associated with dealing with environmental problems in a given geographic locality in a way which transcends jurisdictional boundaries. This emphasis is found for example in Allen et al. (1993) and in Mitchell and Shrubsole (1994). Kay and Regier go beyond this by emphasizing the complex system aspects of ecosystems and socio-economic systems. The advantage of their particular methodology is that is includes as part of the assessment of sustainability, consideration of the ability to regenerate after crisis.

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[1] Balance was introduced in Section 2.3, and adaptability was discussed in Subsection 3.1.3.

Their methodology includes the interrelated activities of analysis of the system of interest, defining the problem at hand, generating scenarios of the future, selecting a scenario and determining ways in which to try to bring it about. There are a number of ways of defining and describing a complex system, so that knowledge of the problem to be resolved is needed to produce a relevant system description. In order to define a problem, there must be some idea of what is desired for the future and how this is different from the present. Determining ways to bring about change may greatly influence which scenario of the future is selected. The activities of the methodology are thus not truly sequential, since they all influence each other.

An important aspect of the methodology of Kay and Regier (2000) is the attention it pays to issues of hierarchy and scale. In a city described as a socio-economic system, the individual human being might be at the lowest hierarchical level, with firms, households and other organizations at higher levels. It is important to describe the system at a number of spatial and temporal scales, even if there is no appropriate firmly definable hierarchical entity. The city may be part of a system of cities. There may be local processes which operate at a range of, say, 20 km, which it is desirable to include in the description. There may be other important processes in a system of cities operating at a range of 200 km. There may be no definable system boundaries at either the 20 km distance or the 200 km distance, so that a true hierarchy in the sense of Simon (1962) does not exist. Nevertheless, the description should include both sets of processes along with an indication of their geographic range. 'Formal' systems can be set up at the 20 km and 200 km distances. The relevant interconnections between systems at a given level in chosen scales need to be described, as well as the interconnections between systems at different levels in the hierarchy.

After hierarchical description, the next step in the methodology of Kay and Regier (2000) is attractor analysis. The notion of attractors comes from chaos theory. A self-organizing, open complex system has a tendency to remain within a limited region of state space, despite changes in its environment. Feedback loops keep a system near an attractor. Provided the system is not moved too far from the attractor by some external influence, there are feedback loops which tend to return it to the attractor. In attractor analysis, one describes the possible attractors for the system, identifying the sources of available energy, material and information sources, and the feedback loops which stabilize the attractors. Desirable attractors are to be identified as possible design choices.

The notion of attractors is problematic for a socio-economic system which is undergoing development. Such a system is constantly changing. It can be imagined as heading for an attractor, which can be equated with 'conservation phase' in Holling's diagram (see Figure 3.1). In the case of a natural ecosystem undergoing development, the conservation phase has very often been observed and described. However, in the case of a socio-economic system, it is not obvious what the attractor is, of indeed whether there is more than one attractor. The notion of attractors was therefore deemed to be of limited usefulness in the present analysis. The previously introduced idea of balance seems to be sufficient for examination of the types of things covered by Kay and Regier (2000) under attractor analysis. That is to say that an examination of balance will reveal the feedback loops which enable the system to maintain its present state, or its present course. It will reveal sources of energy, materials and information. This is the same sort of understanding obtained from attractor analysis.

4.1.1 General Propensities of Self-Organizing Systems

There are certain general tendencies, or propensities, which can be expected in complex, dissipative systems. In their methodology, Kay and Regier (2000) propose looking for the local manifestations of these general propensities in the particular system of interest. In this way, an understanding of the self-organizing processes can be achieved.

In general, over time, a self-organizing complex system will:

(1) capture more resources
(2) make more effective use of resources
(3) build more structure
(4) enhance its own survivability

These propensities are clearly in accordance with the thermodynamic requirement for increasing dissipation over time. Recall that self-organization proceeds only when the dissipation is greater than the dissipation that would occur in the absence of the complexifying changes in the system. Capturing more resources allows the system to grow, thus increasing dissipation. The dissipation processes of the system take place in structures, so that more structure permits the increase in dissipation. More effective, or I would say, more efficient, use of resources permits more structure to be maintained for same input of resources. Enhancement of survivability is a requirement because the structures which permit the dissipation processes must persist long enough for the dissipation to be greater than the dissipation would be in the absence of those structures.

As a general statement of self-organizing propensities, the above list is adequate for very long-run considerations. But the adaptability-efficiency trade-off is ignored. The fact that adaptability can be traded away in order to gain efficiency is not mentioned. The enhancement of survivability is a feature of the self-organization process which needs some qualification. The requirement for enhancement of survivability must be met, but only in a general time-averaged way. Kay and Regier (2000) are aware of this. In fact, one of their criteria for ecosystem integrity is that ecosystems must have the capability of dealing with the birth-growth-death-renewal cycle of Holling (1986). The use of the word 'effective' in list item (2) appears to reduce the need to consider the adaptability-efficiency trade-off. In earlier papers (Schneider and Kay, 1994a, 1994b), the word 'efficient' was used in similar statements.

The adaptability-efficiency trade-off should be included as one of the general propensities of self-organizing systems, modifying item (2) and replacing item (4) in the list of Kay and Regier (2000). In the analysis of this chapter, I have used the following general propensities.

(1) capture more resources.

(2) make more efficient use of resources.

(3) build more structure.

(4) maintain sufficient adaptability to survive in the long-run, with periods of erosion of adaptability to gain efficiency, interspersed with adaptability regenerating, efficiency reducing crises

4.1.2 Sustainability as Ecosystem Integrity

As noted above, the sustainability of an economic ecosystem has been equated with its ecosystem integrity by Kay and Regier (2000). They describe ecosystem integrity with reference to a particular attractor.

Ecosystem integrity consists of:

(1) current well-being (status relative to current attractor)

(2) stress response relative to influences from its environment

(3) capacity to develop, regenerate and evolve

    (a) continue to develop, that is increase its organization relative to an attractor

    (b) regenerate, to deal with the birth-growth-death-renewal cycle, i.e. the Holling four box model (see Figure 3.1)

    (c) continue to evolve, that is switch attractors spontaneously

Several changes were made in this thesis in applying this definition of ecosystem integrity to the sustainability of an economic ecosystem. First, as already noted, instead of using the idea of an attractor, the idea of balance is used as a guide to performing the same sort of analysis as would be done for attractor analysis. Second, since this chapter is concerned with a problem-solving exercise, item (1) was changed to refer to current status with regard to design criteria, rather than with regard to the current attractor. There is a potential difficulty with these two changes taken together, namely that the design criteria may not represent an attainable attractor of the system. However, the difficulty is a practical one rather than a theoretical one. An appropriate analysis of balance, including identification of sources of energy, materials and information, should ascertain, as far as is possible, whether the design criteria are achievable. Precisely the same analysis would be required to determine, as far as is possible, whether the design criteria represent an attainable attractor.

The third change is to replace 'stress response relative to influences from its environment' with 'adaptability'. Recall that adaptability is the ability of a self-organizing system to 'survive' despite the uncertainty of the environment, and that 'survival' only has meaning relative to some description of what constitutes the system (Section 3.1.3). In the case of design, the appropriate system description is based on design criteria. The problems of achieving or maintaining design goals in a complex system were dealt with from an adaptability theoretic perspective in Section 3.3.

The fourth change is that item (3a) is lumped with item (3c). This amounts to lumping phenotypic evolution and genotypic evolution (see Subsection 3.1.1) together under the rubric of 'development'. This avoids a terminological difficulty. The term development tends to mean phenotypic evolution in ecology, but genotypic evolution in economics. Kay and Regier (2000) follow ecological terminology in equating development (i.e. ecological succession) solely with phenotypic evolution.

There are three other points which I think should also be included in a description of sustainability. They are all related to the capacity to continue to develop. The first is that complexity tends to increase with increasing dissipation. Complexification involves the increase in diversity of components and the addition of more hierarchical levels. The second is that the cost of adaptability, in terms of the dissipation required, is greater for more complex systems. And the third point follows from the first two: systems in more uncertain environments cannot achieve as great a degree of complexity. The ideas behind these are all introduced in the previous chapter.

Upon making these changes, a list of four points emerges which should be considered in any description of sustainability.

(1) current status relative to design criteria

(2) adaptability (as ability to remain within design criteria, cf. Section 3.3)

(3) capacity to continue to develop (i.e. phenotypically and genotypically)

  (a) The achievable complexity of the system increases with its dissipation, i.e. its energy degradation rate.

  (b) The cost of adaptability, in terms of dissipation required, increases with complexity.

  (c) The achievable complexity of the system declines with its environmental uncertainty.

(4) capacity to regenerate after crisis

These four points need to analyzed with respect to local manifestations of the general propensities of self-organizing, dissipative systems. Furthermore, the analysis should be carried out at a set of appropriate spatial and temporal scales, so that the relevant hierarchical chararcteristics of the system are included.

4.1.3 Summary

In this section, a methodology for the design of the sustainability of an economic ecosystem was proposed. Following the terminology of Conrad (1983), an economic ecosystem is an ecosystem which contains an economic system. The methodology is based on that of Kay and Regier (2000). The main features are: the importance of hierarchy and scale, general propensities of self-organizing dissipative systems, and the features of sustainability (or integrity) which need to be considered in assessing, or designing, sustainability. The intention was to provide a systematic way to evaluate the possible role of urban water demand management with respect to the sustainability of a city.

4.2 What to Sustain

The idea of sustainability as problem-solving was introduced in Section 1.2. Problem-solving (see Figure 1.1.) involves changing an actual situation into a potential, more desirable situation, by taking action after some sort of modelling process. Before proceeding with problem-solving, it is necessary to know understand the 'actual situation' and the 'potential, more desirable situation', towards which one is aiming. In the case of problem-solving for sustainability, this means that there must be an answer to the question of what should be sustained. However, because there are many perspectives on this question in any society, there will never be a single, definitive answer.

For the Regional Municipality of Waterloo, situated in the Grand River watershed, there have been two statements produced by official government bodies which are helpful in providing some answer to this question. These two statements are in the form of a vision for the future. They have a degree of legitimacy over other possible views in that they were arrived at through processes involving various government agencies, businesses and the public. One of the vision statements is contained in the "Regional Official Policies Plan: Planning for a Sustainable Community" (Regional Municipality of Waterloo, 1998), and the other is in "State of the Grand River Watershed: Focus on Watershed Issues 1996-1997" (Grand River Conservation Authority, 1998). In the following discussion, these will be referred to as the ROPP and the SGRW respectively.

The ROPP gives a statement of what is desired to be in place in the year 2016, or to have happened leading up to 2016. According to the ROPP vision statement, by 2016 the population will be growing mainly due to people moving out of the Greater Toronto Area. Most of the population growth will be in existing urban areas. New infrastructure will be built to keep pace with population growth. There will be continued economic stability, although the economy will be changing and growing. Water conservation and waste reduction will be important to business and residents alike. The demand for water will have been reduced. Farming will remain a primary economic activity within the Region, with rural settlements remaining economically viable. Environmental integrity, in support of the Regional economy and quality of life, will be a priority. Implementation of the Regional water resource protection plan will have reduced the likelihood of contamination of surface water and groundwater. There will be a strong recognition in decision-making of the 'inter-relationships among the economic, social, cultural and natural environments'. The full text of the 'Vision for 2016' is given in Appendix B.

The various items in the statement are in general not given in contrast to the present situation. They are also sometimes presented in an instrumental fashion, i.e. with an emphasis on how things will be done, rather than what is to be achieved. Many of the items in this vision statement refer to the continuation of trends which can already be seen now. Given these features, it is sometimes difficult to tell how, or if, the vision of the future in the ROPP differs from the current situation. Perhaps this is an indication that continuation of the present quality of life in the Region would be acceptable.

Before moving on to the vision statement of the SGRW, a comment on the importance of hierarchy is in order. The previous paragraph referred to economic stability, with a changing and growing economy. This appears to be contradictory, and the ROPP vision statement does not resolve the contradiction. I think a good resolution is that 'economic stability' refers to the economic stability of individuals or households, whereas the growth and change refers to the Regional economy as a whole. What appears to be contradictory in this case, is not, if two different scales of observation are employed.

In the SGRW, ten issue areas were identified in a set of vision statements: population, business development, water supply, water capacity for wastewater discharge, water quality, flooding, fisheries resources, natural areas and biodiversity, outdoor recreation and human heritage. The statements for all ten areas were compiled, and are reproduced as a 'Vision for the Future', in Appendix B. In many of the statements of the 'Vision for the Future', the current high quality of life is recognized. The current quality of life is good and the watershed is an attractive place to do business and to live in. These attributes should be maintained in the future. Growth of human population and economic activity must be managed to ensure that it is beneficial, now and for the future. The economic development which occurs should benefit communities. It is important to value water appropriately and to use it wisely. There needs to be adequate capacity for the Grand River to assimilate wastewater. There needs to be good quality water for rural and urban water supply, and for natural ecological communities. Reduction in flood damage is desired. Tourism has been underdeveloped so far, and should be more encouraged. High water quality in the river and its tributaries should promote a valuable fishery, aquatic recreation such as swimming and boating, and help maintain biodiversity. Human heritage will be valued, and combined with natural heritage, will lead to a sense of community among watershed residents.

In the SGRW, the problems and instrumental issues of achieving the desired vision are kept separate from the vision of *what* is desired. With respect to water resources for cities, several problems are identified. The following problems are listed in the SGRW. Population growth will put more stress on water sources, water supply infrastructure, wastewater treatment infrastructure, and the wastewater assimilation capacity of the Grand River. There are currently about six hundred thousand people in the watershed. This is expected to increase to nine hundred thousand by the year 2021. It is not known whether water resources will be adequate for future population growth and economic development, so that work should be done to determine the capacity of the watershed to supply water, assimilate wastewater and at the same time preserve the health of the natural environment. Wastewater assimilation is seen as a more immediate problem than water supply. River water quality improved from the 1970s to the 1990s, but the improvement has slowed or stopped. Water quality in the river is affected by waste loading, i.e. by the quantity of wastes which are put into the river, whether through wastewater treatment plants or agricultural practices. Reduction of waste loading can be achieved, but at greater cost. Limits to withdrawing water from the Grand River are set in part by water quality criteria. This is done to preserve sufficient wastewater assimilation capacity in the river. The increase in urban water use should be slowed through water efficiency and water conservation programs. There needs to be overall watershed planning to allocate water use between withdrawal uses and keeping water in the river for fisheries, recreation, and the preservation of natural areas. There is no overall watershed planning of water supply, wastewater assimilation and municipal growth, and no strategy for the management of growth. Business development also is not integrated with other planning. Dams built on the river and its tributaries originally primarily for flood control, now must operate under more stringent constraints. Dams are used to ensure adequate flows for water supply and for the assimilation of wastewater, as well as to control flooding. These constraints are to some extent contradictory. There is no longer any provincial funding for dam construction or major maintenance, and there is inadequate funding for water quality monitoring.

The vision statements of both the Regional Official Policies Plan and the State of the Grand River Watershed paint a picture of current economic prosperity. The visions for the future express a desire to continue this prosperity, which depends in part on the water resources of the Regional Municipality of Waterloo and of the Grand River watershed. Both documents cite water demand management as a strategy for achieving the desired future and making it more sustainable. Is it justified to view water demand management in this way? The following analysis takes up this question.

4.3 Analysis

Before proceeding to the analysis of how urban water demand management relates to the sustainability of urban communities, a recapitulation of the framework of analysis developed in Section 4.1 is order. The sustainability of an economic ecosystem (see the revised list in Subsection 4.1.2) consists of the following elements.

(1) current status relative to design criteria
(2) adaptability (as ability to remain within design criteria)
(3) capacity to continue to develop
    (a) The achievable complexity of the system increases with its dissipation, i.e. its energy degradation rate.
    (b) The cost of adaptability, in terms of dissipation required, increases with complexity.
    (c) The achievable complexity of the system declines with its environmental uncertainty.
(4) capacity to regenerate after crisis

In order to evaluate these elements, reference must be made to the propensities of self-organizing, dissipative systems. These are (see Subsection 4.1.1):

(1) capture more resources.
(2) make more efficient use of resources.
(3) build more structure.
(4) maintain sufficient adaptability to survive in the long-run, with periods of erosion of adaptability to gain efficiency, interspersed with adaptability regenerating, efficiency reducing crises

The analysis of sustainability must pay careful attention to hierarchy and scale. The present analysis takes the elements of integrity of the economic ecosystem into account by looking at a set of issues which illustrate the propensities of self-organizing open systems.

The set of issues is: carrying capacity, Jevons' paradox, sources of available energy, complexity, and adaptability.

Carrying capacity is the most obvious issue of sustainability. If a society cannot obtain the necessary energy and materials for its maintenance or growth, then these cannot be sustained. In the case of a city, energy and materials almost all come from the city's natural or socio-economic environment. In considering carrying capacity, the importance of scale becomes evident immediately. There is much confusion about the worth of carrying capacity as an organizing concept. The confusion stems from a failure to account for the effect which increasing societal complexity has on the geographic scale which is needed in an examination of carrying capacity.

The second issue is a generalized form of the Jevons' paradox. As described in the previous chapter (Section 3.2), limits imposed by carrying capacity are quite flexible. A more efficient self-organizing system can cause a greater flow of resources to itself, allowing for greater growth. It can do this provided its competitors do not also increase their efficiency as much or more. Jevons enunciated a special case of this principle in the nineteenth century.

The third issue is the relationship of available energy and societal complexity. Much of the energy used to sustain modern societies is non-renewable, although solar energy remains indispensable for food production. The depletion of fossil fuels is a matter of concern, because the complexity of modern societies depends on greater dissipation than is possible using solar energy alone. As fossil fuels are depleted, their economic value should increase relative to other commodities, resulting in higher energy prices. This will have implications for urban form, the size distribution of cities and the ability to move water over distances.

The fourth issue is adaptability of a city and its environment. This issue is taken up by looking at the independence of a city from its local natural environment. As the city gets larger with respect to its environment, independence decreases. This means that the adaptability of the local natural environment serves less and less to buffer the efficiency and predictability of the city. To keep a handle on predictability, there is an increasing desire to integrate various aspects of city planning, and also to incorporate more and more of the environmental dynamics into planning. Deliberate buffering devices, such as wastewater treatment plants, must be organized at the cost of a higher energy degradation rate, in order to maintain a certain level of independence.

The last issue is that of the capacity to regenerate after crisis. Crises are inherently unpredictable, and socio-economic crises throughout history have not all been of equal severity. Nevertheless, some conclusions can be drawn about the possibility of a crisis brought on by decreasing energy availability.

4.3.1 Carrying Capacity

The carrying capacity of an environment is 'its maximum persistently supportable load' (Catton, 1986). This was discussed in the previous chapter (Section 3.2). For most biological species, 'supportable load' refers to the size of the population. In human societies, there is a trend towards the use of more resources per capita as societies develop. This trend is in agreement with the general propensities of self-organizing systems. So for humans, load does not depend on population alone. In a more economically developed society, humans are effectively larger individuals when it comes to carrying capacity.

A necessary but not sufficient basis of carrying capacity is mass balance. In any open system, material input must equal the sum of material output plus material accumulation within the system. Desired materials are removed from the environment, while unwanted materials are released into it. Mass balance is not sufficient for evaluating carrying capacity, because the environment of a socio-economic system is not simply a storehouse of materials. The environment of a socio-economic system always contains complex self-organizing systems itself. Consequently it can act in surprising ways. It is usual to consider only the natural environment in questions of carrying capacity. I am not going to try to change that usage, but it should be pointed out that the socio-economic environment of a socio-economic system is in many cases as important or more so than the local natural environment as a source of materials.

Technological development is held by some (for example Lenski, Nolan and Lenski, 1995) to have reduced the relevance of carrying capacity. Others, with whom I agree, argue that technological development, and also long-distance trade, have permitted socio-economic systems to be less dependent on local natural resources, but more dependent on natural resources at larger spatial scales (Rees, 1996; Chase-Dunn and Hall, 1997). This is more true for resource[1] supply than for waste disposal. Intentional and accidental disposal of materials affects local environments more than distant ones. Still, there are some waste disposal issues which are global in scale. Atmospheric change through the production of greenhouse gases is an example. Some waste disposal is considered problematic. In other cases, the natural environment assimilates waste in what is generally considered a benign way. But even benign assimilation does not occur without some change in local ecological communities. Local and global waste disposal which is problematic adversely affects a society's ability to self-organize. Resolution of the problems presented by such waste disposal leads to increases material and energy requirements of societal self-organization.

A city gains some of the resources needed to sustain its self-organization directly from its natural environment at various scales outward from the city. Many resources, perhaps most, for a city are taken from natural environments only indirectly, through long-distance trade (as opposed to intra-city trade). One of the distinctive characteristics of water as a commodity is that is tends not to be involved in inter-city trade (Beecher, 1995). This

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[1] I use the term resource here in a general sense, implying any useful commodity which enters the system of interest.

is because of its low price and high transportation cost. Water for cities tends to be taken directly from the local natural environment.

In the 1991 to 2041 period, expected population growth for Kitchener, Waterloo, and Cambridge is 70%, 75% and 86% respectively (Associated Engineering, 1994). Total population of the Tri-City area was 346,000 in 1991. It is expected to reach 606,000 by 2041. Population growth of this sort puts pressure on urban water systems to expand. Water for the Tri-City area comes from wells located within the cities and from the Grand River as it passes through the cities, but also from wells located in the rural townships outside the cities. In the Region's Long Term Water Strategy, Associated Engineering (1994) has proposed several water supply options. The options can be classified into three types: more groundwater wells, an artificial recharge scheme, and pipelines from one of the Great Lakes, either Lake Huron, Lake Erie, Georgian Bay or Lake Ontario. The pipeline options would not mean less dependence on the environment for water, just less dependence on the local environment.

The scale of resource use by society depends in part on its per capita consumption of resources. As noted above, humans in developed societies are effectively larger individuals for the purpose of determining carrying capacity, because they tend to use more resources per capita than in less complex societies. This should not be surprising, given the general propensities of self-organizing, dissipative systems. Urban water demand management appears to go against this trend by reducing the per capita use of water. Not only is water use reduced, but so also is the use of other resources, such as energy for pumping and chemicals for water treatment. Demand management reduces the hydraulic component of wastewater, again leading to a reduction in the use of other resources, such as energy for pumping and mixing in wastewatet treatment plants. The reduction in hydraulic flow produces higher waste concentrations in wastewater, leading to somewhat better performance of wastewater treatment plants (Hydromantis, 1993). Demand management also reduces the resources used by a society in another way. It reduces the need for water supply and wastewater treatment infra-structure.

One might conclude that demand management results in a contradiction of the general propensities of complex, dissipative systems. Efficiency of resource use increases (propensity 2), but overall resource capture (propensity 1) seems to be diminished, and the building of structure (propensity 3) is reduced. In the next subsection, it will be shown that such a conclusion is illusory.

4.3.2 Generalized Jevons' Paradox

The Jevons's paradox was introduced in Section 3.2. Jevons came to the conclusion that increasing the efficiency with which coal was used would lead to a faster rate of depletion of British coal reserves (Jevons, 1865). His statement was specific to a particular resource: "An increase in efficiency in using a resource leads to an increased use of that resource rather than to a reduction in its use." Giampietro et al. (1997) generalized Jevons' original statement to any situation where an increase in efficiency of system components leads to overall system growth. When the efficiency of automobile engines was improved in response to rising oil prices, there was an initial period in which gasoline consumption dropped. Later, however, people tended to increase their leisure driving time and buy larger vehicles such as mini-vans and four-wheel drive pickup trucks (Cherfas, 1991). Increasing the energy efficiency of refrigerators has been accompanied by an upward trend in the size of refrigerators (Khazzoom, 1987).

The generalized Jevons' paradox is most obviously a manifestation of the first two general propensities of self-organizing systems: capturing more resources and becoming more efficient. The examples given also show the third propensity in operation: building more structure.

The generalized Jevons' paradox can also be stated as follows: an increase in efficiency represents an improvement in an intensive variable, which allows room for increase in one or more extensive variables. As discussed in Section 2.5, water demand management generally involves improvement in intensive variables, such as water use per capita. Extensive variables, such as city population and industrial output are not the object of urban water demand management. Does the Jevons' paradox apply to efficiency in water use? There are two possibilities.

The first possibility is that increased efficiency in water use might lead to greater use of water. For example, it might be possible for a family which saves enough water by means of low flush toilets to decide it can afford a swimming pool. This seems an unlikely scenario. Any restraint on installing and operating a swimming pool would more likely pertain to costs other than that of water.

The second possibility is that increased efficiency of water use might lead to greater use of resources other than water. The place to look for a Jevons' paradox with respect to water use efficiency would be in a water intensive industry. If the industry were to use less water per unit of product, it could better afford other production inputs. This could lead to more production. It could also lead to a greater rate of use of material inputs, perhaps even a greater rate of use of water. More water could be used than before, if there were a positive difference between increase in water used due to the expansion in production and the water saved by the water efficiency improvement.

A parallel analysis might be made at the larger scale of a whole city. It is evident that a good urban water demand management strategy actually does lead to reduction in city water use. Therefore the first possibility dealt with above, that of increased water efficiency leading to more extensive water use, is not seen at the level of an entire city. A Jevons' paradox arising from improvements in water use efficiency can instead be expected to manifest itself in increased use of resources other than water. Reallocation of resource use to other segments of society is one of the motives given by Tate (1990) for water demand management (see Section 2.5).

Such reallocation need not stop at the scale of a single city. According to the generalized Jevons' paradox, the reallocation made possible by increased efficiency in water use should lead to growth in overall resource use, with concomitant increase in production of wastes. The Jevons' paradox implies that more emphasis will be given to the short-term aspect, than to the long-term aspect, of the sustainability contradiction.

4.3.3 Complexity and Available Energy

The sources of energy for the maintenance and growth of the cities of Cambridge, Kitchener and Waterloo are the same as for other cities in the developed world. Useful energy is imported into the cities[1] mainly as food, fossil fuels and electricity. Solar energy is of course important in the production of the food imports to cities, but fossil fuels play a very significant role in modern agriculture. The electricity is derived primarily from fossil fuels, nuclear power and to a lesser extent, hydro power.

It is the normal situation to look at the monetary cost of bringing water into the economic system of the city. However, the acquisition of water, its treatment to make the water an economic commodity, and its delivery to customers, always entails a cost in terms of energy, i.e. the rate of energy degradation. Societal energy use has been linked to resource quality use by Hall et al. (1986). Water quality can be expressed in terms of many different parameters, such as hardness, pH, concentrations of various problem substances,

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[1] Aside from socio-economic systems, cities also contain 'natural' ecosystems, lawns, planted and wild shrubs and trees, with associated animals and microbes. As with other 'natural' ecosystems, these run by dissipating the sun's energy, although certain cross-connections with the socio-economic system may be present.

such as iron or pesticide residues. This way of expressing water quality is most useful for the engineer who must devise ways of dealing with any water quality problems. A different way of expressing the quality of water and other resources was proposed by Hall et al. (1986). Their idea was to express the quality of a resource in terms of the amount of energy required to make it an economically useful commodity. In this case, an energy cost view of water quality should be useful. With this view, not only the chemical and physical properties of the source water should be considered as parameters of quality, but also availability of the water. For example, the energy spent on pumping ground water, or transporting water over a long distance by pipeline would be relevant to this notion of quality. It is expected that in the future, the difference in monetary cost of water transported from a distance and the cost of local water will be even greater than it is now.

Applied to an energy resource, this criterion of resource quality sets a limit on what is and what is not an energy resource. Clearly, if more energy is used in getting a barrel of oil out of the ground than can be gained from the barrel of oil, then the oil in the ground is no longer an energy resource. It might still be a resource, say as a source of chemical raw materials, but an energy subsidy from elsewhere would be required to make use of it for that purpose. Hall et al. (1986) have shown that for the case of domestic US oil production, there has been a steady decline in this century in net energy production, as more and more energy is used in exploration and getting oil out of the ground. However, oil from the Middle East still has a very high rate of return on energy invested.

The eventual depletion of fossil fuels was recognized in the nineteenth century by Clausius, one of the formulators of the second law of thermodynamics. Clausius, however, was not concerned about the immediate possibility of such depletion, although depletion still seemed to him to be probable in a time frame 'relatively short compared to the life of nations' (Clausius, 1885, quoted in Martínez-Alier, 1987). In 'Limits to Growth', Meadows et al. (1972) contended that many natural resources would be depleted if there was exponential growth in resource use. There would, as a result, be a collapse in industrial output per capita and in human population. The peak in industrial output per capita would occur about 2010, while the peak in human population would be later, at about 2050. Their model was challenged by many, on the grounds that technological development and resource substitution would overcome the difficulties (e.g. Kahn et al., 1976). Unfortunately, the remarkable achievements of technological innovation which, over the past 250 years, have led to the present level of socio-economic development, have all been based on one strategy: increased energy use. The production inputs, labour, capital and natural resources are highly interdependent quantities, not independent inputs to production as is assumed in standard economic theory (Georgescu-Roegen, 1979). The interdependence was confirmed by Costanza (1980) and Costanza and Herendeen (1984), who investigated the direct and indirect energy costs of labour, capital, natural resources and government services. Substitution among these inputs to production involves shifting the path of energy through the socio-economic system.[1]

There is perhaps a consensus developing with respect to oil depletion, although it may be too early to say. According to estimates by geologists Campbell and LaHerrère (1998), world oil production will peak before 2010. They expect that by the year 2000 the OPEC oil production will rise to about 30% of world production. This will be close to OPEC's 36% production share during the 1973 oil crisis. According to Franco Bernabé, chief executive officer of the Italian oil company, ENI, "There is a great deal of complacency among politicians and economists that the oil problem is over. But despite today's low prices, in the long term we will be back to a high-price scenario in the oil sector." He estimates a somewhat sooner date for the peak in world oil production, between 2000 and 2005 (Banks, 1998). Campbell (1997) expects high oil prices to cause a plateau in production for a number of years before resource constraints start to dominate.

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[1] The independence of these inputs is one of the assumptions of general equilibrium theory, discussed in Section 2.3).

The International Energy Agency of the Organization (IEA) of the OECD (Organization for Economic Co-operation and Development) submitted a report for the G8[1] Energy Ministers' Meeting in March, 1998, which endorsed a view similar to that of Campbell and LaHerrère (Srodes, 1998). The IEA has predicted a peak in oil production in 2010 with a drop to 97% of the peak by 2020 (Campbell, 1999). This does not mean the immediate depletion of oil. Still less does it mean the depletion of natural gas and coal. However, if the energy capture rate of the global economy decreases, one should expect a decrease in the complexity of that economy. It is not likely to be a smooth transition.

Given the importance of fossil fuels to the modern socio-economic systems generally, the monetary cost of energy is bound to increase as fossil fuels are depleted. One conclusion to be drawn from this is that the energy cost of water supply and wastewater treatment will become more important for determining monetary costs in the future than it has been in the past.

One must consider the changing relationship between money and energy in long-term planning. There may be situations where the current monetarily best solution will not remain so. This is not to say that the short-term monetarily best solution can be dismissed. If the money is not available for preferred long-term solutions, or is needed or otherwise desired for other purposes, then a less preferred long-term solution will have to be accepted.

Aside from direct effects on urban water systems, less available and more expensive energy will likely have important long-term impact on the degree of concentration of human populations and on the form of cities. Krugman (1991) presented a simple model of geographic concentration of industry with which to examine the relative importance of economies of scale and resource costs. One of the key factors in his model was the cost of

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[1] The G8 is the association of the world's eight leading industrial countries: Canada, France, Germany, Italy, Japan, Russia, the UK, and the US.

inter-city trade. Cheap transportation costs resulted in higher importance of economies of scale and of historical accident in settlement pattern. Increasing energy cost had the converse effect of promoting a more diffuse settlement pattern and reducing the impact of economies of scale. In this situation, inflation of population projections, mentioned by Robinson (1986) as a motive for water demand management (see Section 2.5), is likely to be more important than in the past.

4.3.5 Adaptability

The components of adaptability (behavioural modifiability, independence, anticipation and indifference) all represent sets of potentials which may or may not prove to be useful. Maintaining a large set of potentials is inefficient, and in self-organizing systems there is a tendency to eliminate such inefficiencies in the course of development by self-organization. The right mix of efficiency and adaptability ideally should be a design choice based on the expected uncertainty of the future natural and economic environments. In practice, the competitive situation may dictate the required level of efficiency. It is possible that higher water prices in the Tri-City area of Waterloo Region may have resulted in a selection of certain types of non-residential water use, as compared to neighbouring cities in the watershed, Guelph and Brantford. If this is the case, it would follow that by reducing the potential water uses in the non-residential sectors, this would be an example of a trade-off of adaptability for efficiency. Whether or not this is a wise choice would have to be evaluated depending on the desired mix of adaptability and efficiency.

As the scale of a society's economic activity approaches more closely the scale of its environment, the linkages between the two become less forgiving. Allen and Starr (1982) discussed the inverse relationship between connectedness and stability. In the terminology of adaptability theory, a system which is larger in a given environment, i.e. an environment of fixed size, has fewer possibilities, therefore less adaptability.

The issue of wastewater assimilation capacity cited above can be used as an example. As a city appropriates more and more of the available wastewater assimilative capacity of a river, each additional unit of wastewater discharged comprises a higher proportion of the remaining assimilative capacity. The entire system, city plus environment, becomes more connected. When nearly the full assimilative capacity is utilized, chance fluctuations in wastewater production can have serious environmental consequences; and chance environmental fluctuations can have serious economic and social consequences.

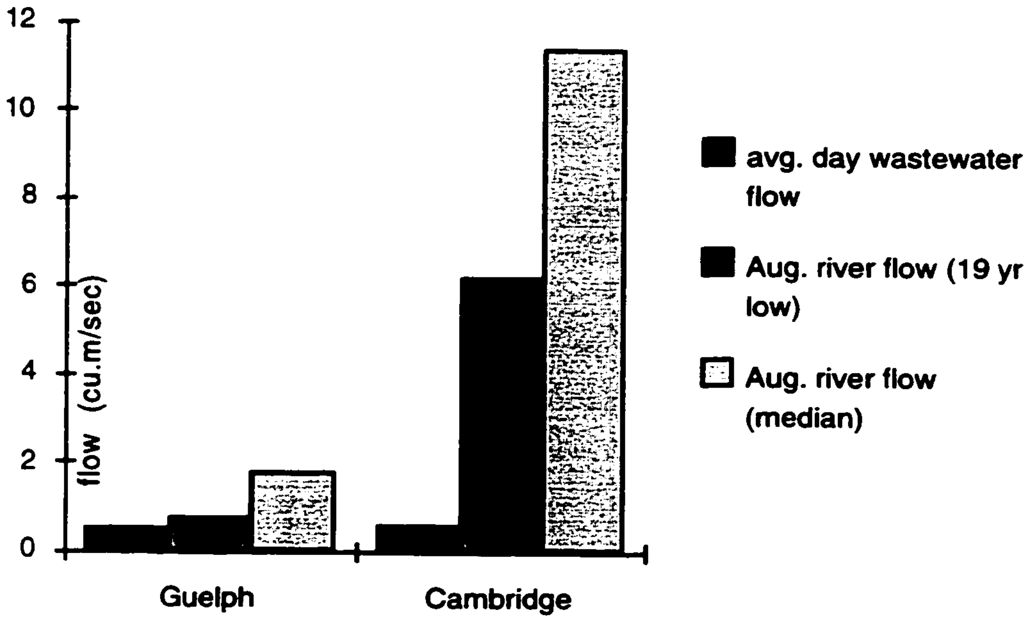

Figure 4.1. Scale of the wastewater flows of Guelph and Cambridge in comparison to the scale of seasonally low flows in the rivers which receive the wastewater.

The scale of treated wastewater flows from Guelph and Cambridge in relation to summer flows in receiving waters is shown in Figure 4.1. The Guelph wastewater flow is similar in magnitude to low summer flows of the Speed River, while the Cambridge wastewater flow is very much smaller than low summer flows of the Grand River (Creese and Robinson, 1996b). Although the actual environmental impact is dependent not only on the relative quantities, but also on the relative qualities of treated wastewater and of river water, there is a very much greater potential for adverse environmental impact in the Guelph situation than at Cambridge. This statement is based on the assumption of independence of the Guelph and Cambridge situations, i.e. that the discharges of treated wastewater upstream of Cambridge (from Guelph, Waterloo and Kitchener) have been assimilated by the time they reach Cambridge.

Despite this, there are strong indications of a potential problem with respect to wastewater treatment even in Waterloo Region. Gore and Storrie (1994) stated in their recent Wastewater Treatment Master Plan for the Region that limits have been identified on the capacity of the Grand River to assimilate wastewater in the period beyond the year 2021, which was the final year of their planning horizon. Upgrading the level of wastewater treatment is one way of dealing with this problem. However, the Region is now engaged in attempting to control non-point source agricultural pollution upstream from the city wastewater treatment plants, with a program of fencing the river against access by cattle and developing buffer strips along streams to reduce runoff from fields. This is intended to improve the water quality in the river. It is a cheaper alternative than upgrading wastewater treatment plants. Still, there are situations where river water does not meet water quality standards regardless of the level of contaminant removal in wastewater treatment plants (Grand River Conservation Authority, 1998).

The issue of connectedness and stability has been put by Conrad (1983) in terms of independence and adaptability. For him, a subsystem of an ecosystem is independent if its dynamic behaviour can be modelled reasonably well using only parameters internal to the subsystem. He showed that in this case, the independence of the subsystem is made possible by the adaptability, unrepresented in the model, of the rest of the ecosystem. Such a subsystem can be organized to maximize efficiency and predictability as long as it remains independent. As a subsystem grows larger with respect to the rest of the ecosystem in which it is situated, it is less likely that its behaviour can be modelled independently of the rest of the ecosystem. This is to say that the adaptability of the rest of the ecosystem is no longer sufficient to buffer the dynamics of the subsystem of interest.

Therefore, in the case of modelling subsystems of ecosystems which are not substantially independent from the whole, there is frequently expressed a desire to include more than just the subsystem of interest in the model. There is a desire to produce models which include externalities. This means integrating the behaviour of subsystems beyond the subsystem of interest into the model. If the set of subsystems incorporated into the new model is still substantially independent of the rest of the ecosystem, it too can be organized to maximize efficiency and predictability. However, if the new model represents a set of subsystems too large to be buffered by the adaptability of the rest of the ecosystem, maximizing the efficiency and predictability of the set of subsystems can be achieved only by sacrificing some of the adaptability of the ecosystem as a whole. The approach of expanding the scope of models to include more subsystems represents anticipatory management (see Section 3.3). Yet this may be precisely the situation that calls for adaptive management.

A desire for overall integrated watershed planning was indicated several times in the 'State of the Grand River Watershed' (Grand River Conservation Authority, 1998). Such planning would include co-ordinating withdrawal uses of water with in-stream uses for fisheries, recreation and the preservation of natural area, and integrating planning for water supply, wastewater treatment and municipal growth. This desire for integration is an indication of greater connectedness of water issues, environmental issues and the development of cities throughout the watershed.

A history of water resources development in the United States was presented by Mar (1998) which contains an interesting and apparently unintentional analogy to Holling's figure 8 (Figure 3.1). He describes an 'exploitation era' (Holling's exploitation phase) where water resources were thought to be virtually unlimited. This was followed by a 'management era' (Holling's conservation phase) where conflicting uses for water had to be dealt with, including environmental uses. The third and final stage is the 'protection era' where the demands are potentially great enough to destroy the supply. The protection era is management to prevent Holling's creative destruction phase.

In addition to a desire for overall watershed planning, there is also a desire for the integration of water supply planning and wastewater treatment planning within the Tri-City area of the Regional Municipality of Waterloo. The practicalities of such integration are dealt with in detail in Chapter 5. Integrated planning of urban water systems is not widespread. At a recent conference on water conservation, CONSERV 96, convened by the American Water Works Association, ten papers were presented on a planning paradigm which is new for water management, called 'Integrated Resource Planning'. Of these eight were about water supply only, one only dealt wastewater as well as water supply and one did not deal specifically with either water or wastewater.[1] In fairness, it must be said that in many cases the integration referred to was integration across institutional boundaries.

The desire for integrated planning is indicative of management in Holling's 'conservation phase', or Mar's 'management era'. In the case of integrating water supply planning with wastewater treatment planning in the Regional Municipality of Waterloo, it seems that limitations imposed by the economic environment of the cities is more important than resource limitations, at least for now. This may change in the near future, with the possibility of a wastewater assimilation problem. There may be cases where the effluent from wastewater treatment plants has better water quality than the body of water which receives the effluent. In this situation, it could be argued that wastewater flows should be increased to increase assimilative capacity of the environment. It is true that water quality objectives could be met by this procedure, but it is a solution of the water quality problem

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[1] The one which included wastewater was Gregg and McReynolds (1996); the ones concerned with water supply only were: Drury (1996), Gardener (1996), Hoffman (1996), Klein et alia (1996), Melendy (1996), Nero et alia (1996), Rodrigo et alia (1996), Ruzicka and Hartman (1996).

which requires active management with attendant energy costs, rather than a solution which enhances the independence of the city from its environment.

4.3.6 Crisis and Renewal

It was shown in Chapter 3 that development by self-organization will always lead to a crisis which will transform a self-organizing, dissipative system by setting back development to an earlier stage. A complex, dissipative system will never be able to remain at what seems like a carrying capacity, judged in only in terms of material balance. In the past, there have been innumerable such crises, small and large, in socio-economic systems. Attempting to use design to avoid this will also produce crisis. For example, it could be decided to under-utilize a resource in order to keep well within environmental carrying capacity. In this way a buffer would be created to insulate a local economy against shocks. However, if the decision to under-utilize at a particular level is rigid, then there is in effect no buffer. There will be a limit on development just as much as a 'natural' limit. So either there is a rigid 'designed' limit, or there is a buffer which will be slowly eroded. In either case, a socio-economic crisis should be expected when the limit is reached. This is why it is important for a description of sustainability to include regeneration after crisis.

What is different about our current historical situation is that economic development has proceeded farther than ever before. We have a lot farther to fall this time. This has been due to our ability to continuously increase the dissipation, i.e. the energy degradation rate, of the world economy. This has been accomplished primarily through the use of fossil fuels. Pimentel and Pimentel (1991) estimated for the US that it might be possible to sustain the 1991 population of about 260 million indefinitely on solar energy, with about half the present energy use per capita, and therefore with lower standards of living. For the current standards of living to be maintained, the population would have to be somewhere in the 40 to 100 million range. It is important to recognize that a decrease in energy degradation rate is not necessary for an economic crisis. It is only necessary that the increase in energy degradation rate reach zero.

On a global scale Duncan (1993) has shown that world fossil fuel energy use per capita is declining. Let us make the assumption, that this is total, not just fossil fuel, energy use per capita. In this situation, it is only if population growth rate exceeds the rate of decline of total energy use per capita could the world economic system continue to develop, i.e. continue to increase its total energy use (not per capita), and so continue to move away from thermodynamic equilibrium. World population *is* increasing at a faster rate than the rate of decline of fossil fuel use per capita. Of course, development could continue with both population and energy use per capita increasing, or with population decreasing but compensated for by increasing energy use per capita. Decrease in both population and energy degradation per capita would not be development (as defined in Chapter 3), would not result in an overall increase in energy degradation rate, and would not be allowed thermodynamically, with an exception. The source of high quality energy which is used by the world economic system is external to that system. The exception would involve the degradation of energy internal to the economic system, i.e. the destruction, at least partial, of the structure and organization of the system itself.

The extent of damage being done to our biophysical environment due to the scale of economic development is a well known environmental problem. There is the possibility of significantly changing the biophysical environment in ways that reduce its long term ability to sustain human society. Urban water demand management alters the allocation of water flows between the biophysical environment and cities. This will help to preserve features of the biophysical environment, at least with respect to water, which may be helpful in recovering after a crisis.

These are, of course, effects of economic development on the natural environment. But what has development done to society itself, apart from increasing its size? What it has done chiefly is to create specialization. There has been geographical specialization, occupational specialization, and specialization of commodities. New products have been invented and old production processes partitioned. Wallerstein (1991) called this increasing the length of commodity chains. It is analogous to increasing the complexity of food webs in ecosystem development. Increasing complexity of food chains or increasing complexity of commodity chains creates more nodes in the ecological or economic network.

It is worth considering what would happen if our society's energy use were to suddenly, or gradually, diminish, say as a consequence of higher energy prices. The complexity of a self-organizing dissipative system is dependent on its energy degradation rate. What commodities that our current water supply and wastewater systems use would no longer be available? Would chlorination still make sense? The function performed by chlorination is vital to making modern cities livable, but what is the energy cost of the process? How would one evaluate automation in water treatment from this point of view? Is automation an energetically cheap form of adaptability, or an expensive one? How complex must an economic system be to maintain the necessary commodity networks for chlorination or for automation? Would there be sufficient energy degradation to maintain the required complexity? I don't have the answers to these questions, but I think it's time to start thinking about them. This effort might be enough if we achieve a controlled, gradual, transformation to a solar energy based society, but it probably isn't. It is probably also necessary to consider whether the commodity networks on which we depend are sufficiently transformable. The continuity through any crisis of the information and expertise of water system and other professionals is also vital. These are tasks that go beyond the capabilities of a single urban water system.

The specialization of commodity networks occurs because of the drive for competitive efficiency. Therefore it doesn't make competitive sense to attempt to reduce the complexity of commodity chains until the last possible moment before a crisis. It would not be competitive to do so. This point has also been made by Ayres and Kneese (1989). The more developed and interconnected an economic system, the more formidable a task this is and the higher the cost. Another part of this competitive bind is that even by taking on the task of analyzing the situation and planning for an expected reduction in energy use, a society loses efficiency. It may lose out to more efficient neighbouring societies, and so lose the economic means of continuing such research.

Technological change is one of major ways by which the complexity of commodity chains is increased. Water demand management can involve technological change. An example of such change is the replacement of conventional toilets with ultra low-flush toilets. A change in technology of this type results in greater efficiency: water pumping is reduced; water treatment costs are reduced; and even an improvement in wastewater treatment may result. However, this technological change does not involve any new specialization. The materials and components of ultra low-flush toilets are not different or not greatly different from those of ordinary toilets, so that there is no diversification of commodity chains required for their fabrication. Such technological change does not reduce the future transformability of an economic system.

4.4 Conclusions

In this chapter, methodology for dealing with the sustainability of economic ecosystems was created based on the work of Kay and Regier (2000) and Conrad (1983).

It is now possible to describe the role of urban water demand management with respect to the sustainability of economic ecosystems. The order of points in the description follows that laid out in the methodology.

(1) current status relative to design criteria

- Demand management helps to ensure that cities are adequately supplied with water. This helps to maintain the well-being of individuals and households.

- Demand management reduces water-taking from the environment. This helps to achieve the vision of local participants with respect to what is desired in the local natural environment, i.e. surface water suitable for Grand River fishery, outdoor recreation and a healthy natural environment.

(2) adaptability (as ability to remain within design criteria)

- Demand management is indirectly (due to promotion of local and global economic development) detrimental to global ecological and resource conditions.
- Water demand management may select for certain types of business activities. This may reduce a city's economic adaptability, if the range of possibilities for future city development is reduced.

(3) capacity to continue to develop

- Demand management results in greater efficiency of resource use. This promotes economic growth and development.

(4) capacity to regenerate after crisis

- Local carrying capacity is not particularly important in the present global economy because so many inputs to cities come from far away. However, local carrying capacity would become more important after a crisis. By disturbing local natural habitats less, water demand management helps to preserve some local ecological and other local natural resource conditions helpful to recovery after crisis.
- Socio-economic crisis involves a rather sudden decrease in societal complexity. Changes which reduce complexity before a crisis might seem like worthwhile long-term goals, but are likely to be competitively disadvantageous in the short-term. Most demand

management strategies do not seem to contribute directly to the complexification of socio-economic systems.

A need for more integrated planning is likely to be felt in systems which are approaching the limits of development, due to the increase in connectedness which occurs in such systems. If integrated planning is carried out solely for the purposes of improving predictability, control and efficiency, then it falls within the paradigm of anticipatory management (Section 3.3). Anticipatory management becomes increasingly more prone to crisis as the degree of connectedness of a system increases. If integrated planning accepts limits on predictably, control and efficiency, but attempts to ensure that unpredictability can be handled in relatively benign ways, then it follows the paradigm of adaptive management. Water resource planning in the Grand River watershed needs to be evaluated to see if it is an appropriate mix of anticipatory management and adaptive management for the current situation.

Crises of various sorts have been mentioned, from socio-economic crises resulting in human population declines, to crises in spruce budworm spraying programs. One of the largest looming crises at present could result from the depletion of oil reserves. The currently developing consensus is that oil production will peak within the decade. This is well within the planning periods for water supply and wastewater treatment in the Regional Municipality of Waterloo. Steps should be taken now to assess the impact of a leveling off and decline in oil production, and to find ways of mitigating the effects.

5

Integrating Demand Management in Planning: A Case Study

The idea of demands for water and wastewater service as expected flows was introduced in Section 1.1. As expected flows, demands are useful for design purposes. However, it is only historic demands, 'expected' only in the statistical sense, which can be evaluated with any certainty. Historic flows are typically the basis for establishing design flows. Demands are measured and expressed as flows over a given time period. Thus the term 'average day demand' typically refers to an annual flow in water system planning. The term 'maximum day demand' refers to a daily flow, i.e. the flow on the day of the year when demand is highest. However, both average day water use and maximum day water use are commonly expressed in 'per day' units. The common units allow for easy comparison, but give the illusion that both are daily flows.

Urban demand for water is strongly seasonal; demand is higher in the late spring and summer than at other times of the year. The water supply subsystem must be designed to meet the summer peak demands. Demand for wastewater treatment, in the southern Ontario climate, is not seasonal. There are storm-related peak flows of wastewater, even in the Tri-City area where storm sewers are separate from sanitary sewers. These do not show a seasonal pattern.

Until the early 1990s, the Region's water supply came entirely from groundwater wells. Starting in 1992, this supply was augmented by taking water from the Grand River. The Long Term Water Strategy (Associated Engineering, 1994) for the Region identified several possible water supply sources to meet the requirements of the cities to the year 2041. The options include an aquifer recharge scheme and several pipeline options from one of the Great Lakes. The aquifer recharge scheme involves pumping Grand River to a natural aquifer, treating it and storing it there during periods of high river flow, and recovering it when it is needed. High river flows occur in the winter and spring, when demand for water by the cities is at its lowest. The water would be recovered during the summer, when cities' demands are highest. Ways are being found to supply water to the cities, but there is a trend toward increasing complexity in the manner of supplying water. Accompanying this is increasing cost. It is not surprising that cheap alternatives are exhausted first. So for water supply, there seems to be ample carrying capacity for projected city growth, although at increasing cost, but for wastewater assimilation, the case is less clear.

The Regional Municipality of Waterloo started to take an interest in water demand management in the late 1970s (Robinson, 1986). Efforts have been directed at modifying or replacing water-using fixtures, at public education, at lawn watering, and at the use of water for industrial once-through cooling. The Region does not have the power to locally create or modify building codes to be different from the Ontario building code, so for many years the installation of water efficient fixtures could not be made mandatory, even in new structures. The Region therefore adopted a financial incentive program aimed at reducing use in existing buildings. Specific programs implemented include retrofitting toilets and showerheads to reduce water use, and replacing standard toilets with low-flush and ultra low-flush toilets. On January 1, 1996, 6 L per flush toilets became the Ontario Building Code standard for new buildings.

A diagram of water flows in an urban water system is shown in Figure 5.1 It can be seen that reduction in water use will have ramifications for wastewater treatment. This chapter is concerned with how water demand management is integrated into the water system planning process, using the Regional Municipality of Waterloo as a case study.

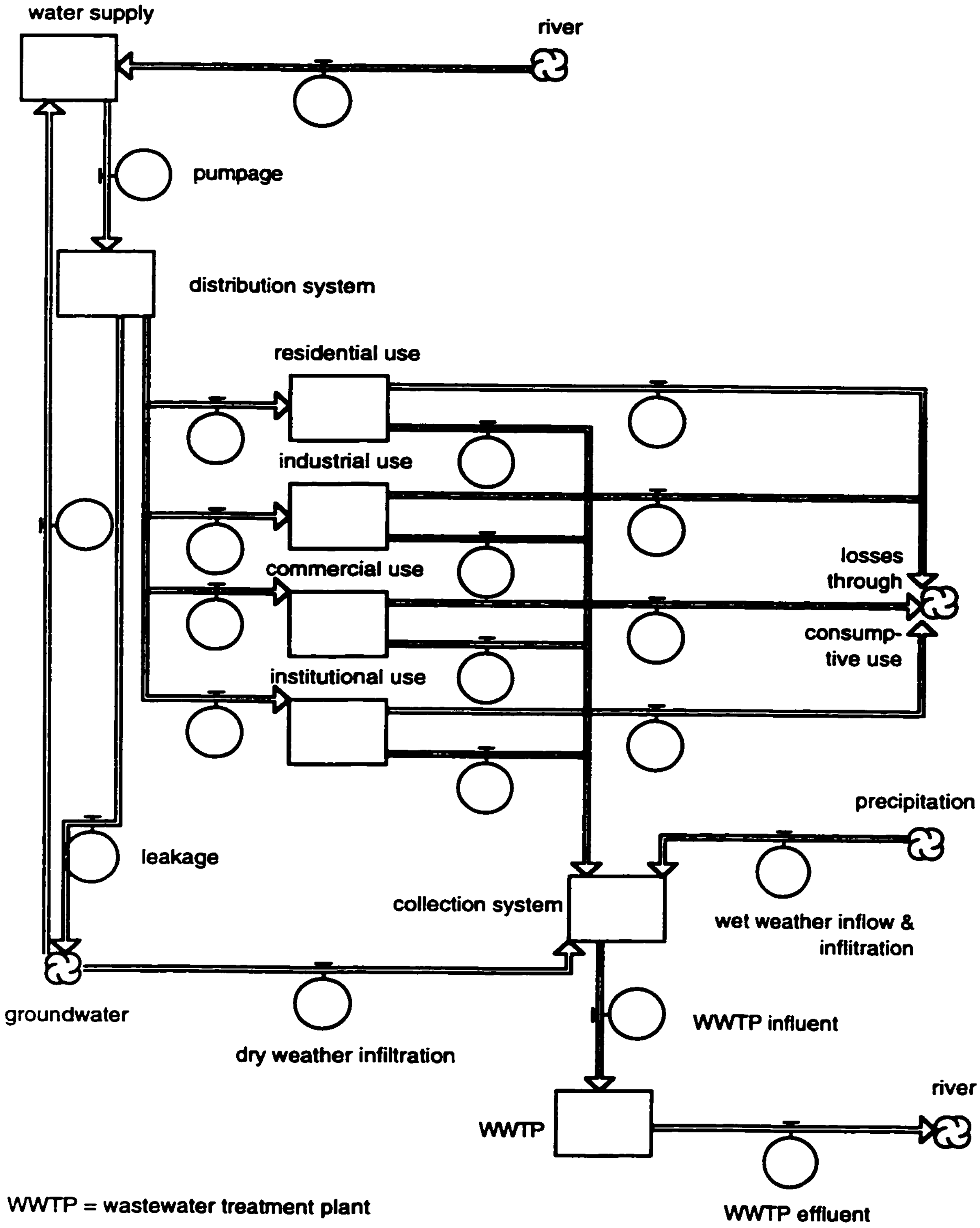

Figure 5.1. Water flows in a generalized urban water system. (Diagram drawn with the STELLA simulation application. See Appendix for a brief description of STELLA.)

Integrated planning of the provision of water, water use and waste water treatment is not common municipal planning practice. This was identified by Robinson et al. (1984). Demand management intended to affect water supply expansion will also have an effect on wastewater treatment. Probably because water demand management is not widely practised, it is likely to be poorly integrated into the planning process.

Recently the Regional Municipality of Waterloo was in the position of having initiated two concurrent planning studies, one dealing with water supply and the other dealing with wastewater treatment. The Region had hired a consulting firm to do a master plan for wastewater treatment and another firm to do work on a water supply plan. In 1994, the Wastewater Treatment Master Plan had been completed in draft form (Gore and Storrie, 1994), and the report of the first phase of the Long Term Water Strategy was also completed (Associated Engineering, 1994). In the following analysis, these two reports are referred to as the WTMP and the LTWS respectively. It is important to recognize that at the time that this analysis was carried out, these two studies were in different stages of completion. A spread-sheet model integrating these two studies was used to demonstrate that a more integrated view of the Region's water system would lead to different timing of system expansions and to a different capital cost picture. A report on this case study was submitted to the Regional Municipality of Waterloo (Creese, 1995). Since 1994, the Region has completed its Water Efficiency Master Plan, which dealt with these issues of integrating demand management measures with water supply and wastewater treatment planning.

My analysis reported that slightly different population data were being used in the two studies.[1] This was subsequently corrected by the Region. In both studies there was the recognition that water demand management can delay the expansion of both water supply

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[1] Credit for the discovery of the differing populations goes to the students of Environment and Resources Studies 375i, 'Integrated Resource Planning', Winter term, 1994, University of Waterloo.

systems and wastewater treatment systems and thus postpone capital costs. However, neither study made a quantitative effort to evaluate the effects on wastewater treatment. Forecasted wastewater flows were estimated in the WTMP in the usual manner, based on historical per capita wastewater flows, not on water use. This meant that declining water use forecasted in the LTWS, due to demand management measures and other factors, was not reflected in the WTMP. In the LTWS, the benefit/cost analysis of water rates acknowledged that the effects of delaying the expansion of wastewater facilities were not considered. The LTWS proposed a toilet replacement program for the Cambridge-Kitchener-Waterloo area which would be completed in the year 2011. By extending the completion year to 2018, the year when the next water supply expansion would be needed, the present value of the toilet replacement program could have been reduced. Even though both water use efficiency and supply management options were dealt with in the same study (LTWS), these two aspects were not optimally integrated. Nor had the WTMP been completely integrated with the LTWS.

The first section in this analysis considers the issue of a common planning horizon. The second examines the extensive variables used in demand forecasting, e.g. population. The third contains an analysis of the intensive aspect of demand, i.e. demand per capita for water and for wastewater treatment. The fourth section of the analysis looks at costs of capacity expansions, particularly changes in expansion costs due to differing forecasts of intensity of demand. After the analysis, conclusions are drawn about consistency of data, methodology and ways to achieve better integration.

5.1 Time Horizon of Plans

The planning period for the LTWS was the 50 years from 1991 to 2041, while the planning period for the WTMP was the 30 year period from 1991 to 2021. In the final subsection of the WTMP (p.7-4) it was stated that limits have been identified on the capacity of the Grand

River to assimilate wastewater in the period beyond the year 2021. By implication it is doubtful that the Grand River can assimilate the wastewater flows implied by the water supply expansions contemplated in the LTWS, although neither report contained this explicit conclusion. This is a prime example of the need for integration in planning. Gore and Storrie is to be commended for including this information in their report, since there was no need for them to consider anything beyond their 30 year frame of reference.

A further time horizon issue is raised in Section 5.4. The issue relates to the difficulty of comparing options when there are no proposed expansions within the planning period or when particular options delay an expansion to beyond the time horizon but other options do not.

5.2 Extent of Demand

Human impacts are related to extensive quantities such as population, and intensive quantities such as resource use per capita. Population is used in both studies as an index of the extent of demand. For the Tri-City area, the LTWS also uses industrial land acreage, commercial land acreage and institutional land acreage. Although the numbers were quite similar, there was a difference in the population forecasts of the WTMP and the LTWS, especially in the townships (North Dumfries, Wellesley, Wilmot).

Taking the LTWS and the WTMP as finished products, the following relationships were used to relate population figures:

serviced water population = base population - unserviced water population

serviced wastewater population = base population - unserviced wastewater population

The LTWS gives base population forecasts (p.2-11) and forecasts for unserviced populations with respect to water supply (p.2-13), while the WTMP gives serviced populations (p.3-6,3-7) for wastewater treatment.

Three base population areas, Woolwich Township, the City of Cambridge and Wilmot Township, are served at present by more than one wastewater treatment plant (WWTP). Table 5.1, Table 5.2 and Table 5.3 give the proportional breakdown of serviced wastewater population into WWTP service areas.

Table 5.1. Proportion of Woolwich serviced wastewater population served by the Elmira and the St. Jacobs WWTPs.

	1991	2021
Elmira	0.847	0.846
St. Jacobs	0.153	0.154

Table 5.2. Proportion of Cambridge serviced wastewater population served by the Hespeler, the Preston and the Galt WWTPs.

	1991	2021
Hespeler	0.165	0.201
Preston	0.208	0.159
Galt	0.628	0.640

Table 5.3. Proportion of Wilmot serviced wastewater population served by the New Hamburg and the Baden WWTPs.

	1991	2021
N. Hamburg	0.750	0.750
Baden	0.250	0.250

Base populations for 1991 are not given in either report. In order to estimate them, a method was used which was described in the WTMP. In the WTMP, the average annual population increase from 1991 to 2016 was used to project the 2021 populations serviced for wastewater (WTMP, p.3-2). The type of extrapolation is not mentioned, but it was assumed to be linear. The same technique was used here on the base populations, using the average population increase from 1996 to 2021 to obtain estimated 1991 base populations. The unserviced populations for wastewater treatment can then be determined for the years 1991 and 2021 by subtracting the serviced population from the base population. The results are presented in Table 5.4. The value of -2,539 for Waterloo in 1991 is not as strange as it seems, since wastewater from the Bridgeport area of Kitchener is treated at the Waterloo WWTP. Note that some wastewater unserviced populations are quite different from the corresponding water supply unserviced populations. Wilmot Township in 2021 is particularly noteworthy. Lehman and Associates (1992, p.36) forecasts that 927 lots unserviced for wastewater will be developed by 2021. This seems inconsistent with an increase in unserviced wastewater population of about 6,000 from 1991 to 2021.

Table 5.4. Forecast of unserviced populations.

	wastewater 1991	wastewater 2021	water supply 1991-2021
Woolwich	8,759	6,438	8,500
Waterloo	-2,539	-610	0
Kitchener	1,957	1,740	0
Cambridge	1,945	798	0
Wellesley	6,931	5,885	6,800
Wilmot	6,813	12,953	6,000
N. Dumfries	4,589	5,178	4,400

5.3 Intensity of Demand

For the intensity of water use, the LTWS produced a series of 'adjusted consumption factors' (LTWS, p.2-17). These were used to find unmodified demand for water. Similarly, the WTMP used 'design per capita flow' (WTMP, p.3-5) to find demand for wastewater treatment. In an integrated approach, it would be helpful to know what proportion of water used is subsequently treated as wastewater, and how much does not enter the wastewater treatment subsystem. Identifying a 'design per capita flow' from historical records does not help in fostering this kind of understanding. This is particularly evident for the three cities, Waterloo, Kitchener and Cambridge. For the Tri-City area, the LTWS divides demand up into residential, industrial, commercial and institutional sectors, whereas the WTMP uses aggregate demand. For comparison, aggregate daily per capita demand for water was calculated using information from the LTWS. This is shown in Table 5.5 along with the design wastewater flows from the WTMP. In each city, there is a significant decline in per capita water use as time progresses. This decline is due to projected changes in land use (industrial, commercial and institutional) and is not reflected in the WTMP design per capita flows, which are constant throughout the planning period. In the subsequent analysis in this section, the WTMP design flows are considered to be start-of-period (1991) flows.

Table 5.5. Comparison of aggregate daily per capita demands. Water use and wastewater flow (underlined) in L/person/day for Waterloo, Kitchener and Cambridge.

<table>
<tr><th></th><th>1991</th><th>1996</th><th>2001</th><th>2006</th><th>2011</th><th>2016</th><th>2021</th></tr>
<tr><td>Waterloo</td><td>360</td><td>358</td><td>354</td><td>350</td><td>346</td><td>341</td><td>338</td></tr>
<tr><td></td><td colspan="7">500</td></tr>
<tr><td rowspan="2">Kitchener</td><td>428</td><td>418</td><td>412</td><td>411</td><td>408</td><td>403</td><td>398</td></tr>
<tr><td colspan="7">420</td></tr>
<tr><td>Cambridge</td><td>569</td><td>550</td><td>539</td><td>534</td><td>529</td><td>520</td><td>512</td></tr>
<tr><td></td><td colspan="7">Hespeler: 380
Preston: 550
Galt: 600</td></tr>
</table>

For the purpose of integration of planning, water use can be broken up into two components, water use from which wastewater production results, and water use which does not. The latter can be called consumptive water use. Similarly, wastewater flow can be broken into two components, wastewater produced from water use or base wastewater flow, and inflow and infiltration (I/I). The component tying water use and wastewater flow is base wastewater flow. The following equations summarize this.

$$\text{water use} = \text{base wastewater flow} + \text{consumptive water use} \qquad \text{eq. 5.2}$$

$$\text{wastewater flow} = \text{base wastewater flow} + \text{I/I} \qquad \text{eq. 5.3}$$

Proportions of wastewater flows which are inflow and infiltration are available from the WTMP. However, if base wastewater flow changes in relation to inflow and infiltration, treating these components as proportions is not appropriate. In this analysis, they were converted to flows per capita, even though it is not clear that a per capita basis is appropriate either. The WTMP (p.6-4) notes that allowance is made for infiltration during sewer design in terms of litres per hectare per day. If population density within a city is uniform then treating infiltration on a per capita basis is reasonable. Inflow, however, is likely different in different sections of a city, depending on the age of buildings and the city bylaws in effect at the time of building construction. New subdivisions can probably be expected to have lower inflow rates than old ones. Inflow rates per capita should therefore likely decrease with time. However, since no information was available on this, it was assumed that, in the absence of deliberate inflow and infiltration reduction programs, inflow and infiltration per capita would remain constant over the entire planning period. Table 5.6 organizes water use and wastewater flow components for the initial year of the planning period, 1991. Inflow and infiltration data from 1989 and 1990 are used, but are assumed to be in the same range as would have occurred in 1991. Note that in water supply planning areas served by more than one WWTP (Woolwich, Cambridge and Wilmot), it was necessary to make an assumption about the distribution of water use. Due to lack of information, the assumption was made that water use was uniform throughout each area. For example, daily water use per capita in the Cambridge subareas, Hespeler, Preston and Galt, was assumed to be a uniform 569 L/person/day.

Table 5.6. Volume balance of design flows for water use and wastewater treatment (L/person/day).

	water use (1991)	design wastewater flow	inflow and infiltration	base wastewater flow	consumptive water use
Elmira	525	450	104 - 140	311 - 347	179 - 215
St. Jacobs	525	550	242 - 275	275 - 308	217 - 250
Waterloo	360	500	140 - 145	355 - 360	0 - 5
Kitchener	428	420	50 - 59	361 - 370	58 - 67
Hespeler	569	380	95	285	284
Preston	569	550	264 - 275	275 - 286	283 - 294
Galt	569	600	36	564	5
Wellesley	121	400	120 - 196	204 - 280	-159 - -83
N. Hamburg	344	350	>70 - >74	<277 - <280	>64 - >68
Baden	344	480	206 - 226	254 - 274	70 - 90
Ayr	221	300	87 - 99	201 - 213	8 - 20

From Table 5.6, the proportion of water used which becomes wastewater (base wastewater flow) and the proportion which does not (consumptive water use) can be calculated for the initial year of the planning period. These proportions are reported in Table 5.7. The WTMP used a different approach. In it, a typical (not measured) value of the proportion of water use becoming wastewater was assumed to be 85%, which was then modified for known industrial water use patterns within each service area. The 85% value should apply to winter daily water use, whereas the numbers in Table 5.7 are based on average daily water use. For comparison, winter daily water use is likely to be about 90% of average daily water use. The numbers in Table 5.7 should therefore be near 76% (= 90% x 85%). Note that in most cases the numbers are not close to 0.76. The proportions for Waterloo, Galt and perhaps Ayr are also suspiciously high and require some explanation. The fraction of used water not entering the wastewater treatment system seems unreasonably high for Elmira, St. Jacobs, Hespeler and Preston. In Wellesley, base wastewater flow was greater than water use, necessitating negative consumptive water use.

A possible explanation is that in Wellesley, there is significant use of non-municipal water which is subsequently treated in the WWTP. This however, is not borne out by the unserviced population numbers (see Table 5.4).

Table 5.7. Proportion of water use which becomes wastewater and proportion of consumptive water use (1991)

	base wastewater flow	consumptive water use
Elmira	0.59 - 0.66	0.34 - 0.41
St. Jacobs	0.52 - 0.59	0.41 - 0.48
Waterloo	0.99 - 1.00	0.00 - 0.01
Kitchener	0.84 - 0.86	0.14 - 0.16
Hespeler	0.50	0.50
Preston	0.48 - 0.50	0.50 - 0.52
Galt	0.99	0.01
Wellesley	1.69 - 2.31	-1.31 - -0.69
N. Hamburg	<0.80 - <0.81	>0.19 - >0.20
Baden	0.74 - 0.80	0.20 - 0.26
Ayr	0.91 - 0.96	0.04 - 0.09

For the purpose of this analysis, the above results were accepted, including the unlikely ones, in order to proceed with the analysis. It should be recognized, however, that the specific results, although not the methods used, in the remainder of this analysis are in doubt due to the character of the data.

The analysis has now been taken to a point where new projections of aggregate per capita wastewater flows, based on water use projections, are possible. Average day water use was projected as in the LTWS by multiplying consumption factors by projected populations, industrial land areas, commercial land areas and institutional land areas. Projected water use was then divided by water supply serviced populations to obtain aggregate water use per capita. The changing patterns of industrial, commercial and institutional water use in the Tri-City area are likely to result in changes over time in the proportions indicated in Table 5.7. However, in the absence of data, these were taken as constant over the planning period. Therefore, the average proportion of water use appearing as base wastewater flow was calculated from Table 5.7 and used to convert water use per capita to base wastewater flow per capita. To obtain total wastewater flow per capita, average per capita I/I from Table 5.6 was added to the base wastewater flow per capita. These revised design wastewater flows per capita are presented in Table 5.8. Note that I/I per capita is likely to decrease over the planning period, assuming reasonable maintenance of the existing wastewater collection system so that I/I per capita in the existing system is kept more or less constant by replacing sewer mains regularly. This is because illegal cellar and footing drain connections to the sanitary sewer system are less likely to occur in new residential areas. Quantifying such changes in I/I was beyond the scope of this analysis, however. A constant I/I per capita was used, which is a conservative approach. It can be seen in Table 5.8 that within the Tri-City area, the design wastewater flows per capita are no longer constant over the planning period. They decrease by 4% to 9% from 1991 to 2021. This is because they now reflect the changing land use patterns (industrial, commercial, institutional) indicated in the LTWS.

A second revision of design wastewater flow per capita was undertaken to account for the effects of the plumbing code modification initiated by the Province of Ontario in January, 1996. Table 2-19 in the LTWS gives the percentage reduction in residential base water use expected to occur as a result of this change. A methodological issue arises from the use of a percentage. The implication is that, say in Kitchener where residential average day demand is given as 266 L/person/day, the savings would be more than in Cambridge, where the corresponding demand is only 227 L/person/day. It is much more likely that toilet flushing per capita, and therefore savings from the plumbing code change, are uniform across communities. Water savings could be better modelled in terms of

Table 5.8. First revision of design wastewater flows per capita, calculated using additional information from the LTWS for Waterloo, Kitchener, Hespeler, Preston and Galt (L/person/day).

	1991	1996	2001	2006	2011	2016	2021
Elmira	450	450	450	450	450	450	450
St.Jacobs	550	550	550	550	550	550	550
Waterloo	500	498	493	490	486	481	477
Kitchener	420	412	407	406	403	399	395
Hespeler	380	370	364	362	359	355	351
Preston	550	541	535	533	530	526	522
Galt	600	581	570	566	560	551	543
Wellesley	400	400	400	400	400	400	400
N.Hamb.	350	350	350	350	350	350	350
Baden	480	480	480	480	480	480	480
Ayr	300	300	300	300	300	300	300

L/person/day than as a percentage of water use. One reason why the effect of plumbing code modification (and fixture replacement programs) was not included in the LTWS for the Townships was that the characteristics of demand had not been adequately evaluated (LTWS, p.2-30). If forecasted savings were modelled as L/person/day, this methodological obstacle would be removed. In this analysis, an average per capita residential water use was calculated, weighted by 1991 water supply serviced populations, for those areas for which the LTWS supplied estimates of residential, as opposed to aggregate, per capita water use, i.e. Waterloo, Kitchener and Cambridge. The 25% saving attributable to the plumbing code change was applied to this weighted average, giving a water saving of 60 L/person/day. This saving was applied to all population increases occurring after the implementation date of the plumbing code change, i.e. to all population increases after 1995. The proportion of this water saving passed along to wastewater treatment was assumed to be 100%. Design wastewater flows per capita were modified accordingly. These are presented in Table 5.9. In this table, design flows per capita for the year 2021 are 5% to 12% lower than corresponding design flows in the WTMP. It is assumed other water using practices and technologies remain constant (for example that there are not increased numbers per capita of pools, jacuzzis, and dishwashers), so that the net effect of the reduction brought about by the change in toilets would remain.

Table 5.9. Second revision of design wastewater flows per capita, accounting for the plumbing code change (L/person/day).

	1991	1996	2001	2006	2011	2016	2021
Elmira	450	449	442	437	432	428	425
St.Jacobs	550	549	542	537	532	528	525
Waterloo	500	497	488	481	474	465	459
Kitchener	420	411	402	398	392	385	378
Hespeler	380	369	360	354	348	341	336
Preston	550	540	530	524	516	507	499
Galt	600	581	565	557	548	536	526
Wellesley	400	397	386	379	373	368	365
N. Ham.	350	348	339	332	326	321	319
Baden	480	478	469	462	456	451	449
Ayr	300	298	289	282	276	271	268

The last issue with regard to the intensity of demand is to determine peak per capita water use. The LTWS makes use of 'peaking factors' (LTWS, Table 2-12 and p.2-19). These are factors by which average day water use is to be multiplied in order to calculate peak period (day or week) water use. A difficulty with this method is that certain water use efficiency measures apply to mainly average day use while others apply mainly to peak period water use. It is therefore important to separate average day use from peak period use. This point has also been noted in the LTWS (p.2-18). In this analysis, peak period additional use, i.e. peak period water use in excess of average water use, was calculated. This is shown in Table 5.10. The peak period additional use per capita was subsequently used in forecasting peak period demands (Section 5.4).

Table 5.10. Calculation of peak period additional use per capita (expressed on daily basis).

	multiplicative peaking factor (ratio)	average day water use (L/person/day)	peak additional water use (gal/person/day)
Woolwich	2.00	525	525
Waterloo	1.28	218	61.0
Kitchener	1.50	236	118
Cambridge	1.52	266	138
Wellesley	3.00	121	242
Wilmot	2.00	344	344
N. Dumfries	2.25	221	276

5.4 Cost of Expansions

With revised design flows for wastewater treatment plants, it was now possible to construct timetables for the expansion of wastewater treatment plants and water supply systems. Several timetables were constructed to represent several scenarios with regard to inflow and infiltration remediation and water use efficiency. In constructing timetables, peak period water demands for the Tri-City area were calculated by simply adding together the peak period demands of Woolwich, Waterloo, Kitchener and Cambridge. This is a conservative approach, since the peak additional water use per capita previous calculated (see Table 5.10) was for the peak day for Woolwich and for the average day in the peak week for the Tri-City area (Waterloo, Kitchener and Cambridge). The resultant peak period use forecasts are intended to be for the average day in the peak week, so the Woolwich peak use figure should be reduced by some unknown factor to convert it to a weekly basis and to account for the non-coincidence of peaks between Woolwich and the Tri-City area. The issue of non-coincidence of peaks also applies within the Tri-City area, i.e. to Waterloo, Kitchener and Cambridge, but it is not clear whether or not this has already been accounted for in the LTWS, Table 2-12.

In Table 5.11, the scenarios produced in this analysis are compared to the 'reported scenario' obtained from the WWTP and the LTWS. The 'integrated scenario' of Table 5.11 is the one obtained from the present analysis described to this point. It includes the effect on wastewater flow of the declining water use per capita implied in the LTWS for the Tri-City area and also the effect of the plumbing code modification on water use and wastewater flow in the townships as well as the Tri-City area. The remaining scenarios in Table 5.11 are modifications of the 'integrated scenario' in accordance with various options of water use efficiency or inflow and infiltration reduction. Although the timing of the events may be different, the same expansion and/or amalgamation strategies were used in all these scenarios as those recommended in the WTMP. The water supply expansion strategies used in developing Table 5.11 are, for the Townships those of the LTWS, and for the Tri-City area the traditional strategy with groundwater recharge. A discrepancy was found in the LTWS concerning the New Hamburg - Baden water supply. On p.3-3, the LTWS states that the capacity will be at 1.2 migd (5.5 thousand cubic meters per day) by 1996. On p.3-6, it indicates that additional supplies of 1.2 migd will be needed in 2016; it should read in both the text and in Figure 3-1 that an additional 1.2 migd in 1996 is needed and 0.7 migd (3.2 thousand cubic meters per day) in 2016.

Expansion schedules corresponding to two programs of I/I reduction were determined. The first program considered was 50% reduction of I/I and the second was reduction of I/I to 20% of received wastewater. In the latter program option, there was no reduction for a particular WWTP if its level of I/I was already below 20%. The WTMP suggests that I/I reduction be a priority and states that a level of I/I above 20% is generally considered significant (WTMP, p.6-10). It can be seen from Table 5.11 that reduction of I/I can lead to considerable delay in expansion of WWTPs. However, I/I reduction was

Table 5.11. Timing of water system expansion. WS - water supply; WWTP - wastewater treatment plant

	reported scenario	integrated scenario	I/I reduced by 50%	I/I reduced to 20%	fixture replacemt	I/I to 20%, fixt. replacemt
expand Tri-City-Elmira-St. Jacobs WS	2018	2013	2013	2013	2020	2020
close Elmira WWTP	1998	2003	2009	2006	2006	2011
close old St. Jacobs, open new SJ-E WWTP	1998	2001	2009	2006	2003	2011
expand Waterloo WWTP	after 2021	after 2021	after 2021	after 2021	after 2021	after 2021
expand Kitchener WWTP	after 2021	after 2021	after 2021	after 2021	after 2021	after 2021
expand Hespeler WWTP	2010	2021	after 2021	after 2021	after 2021	after 2021
close Preston WWTP	This WWTP to be closed for maintenance reasons, not because its capacity will be exceeded.					
expand Galt-Preston WWTP	? (2009)	2019	after 2021	after 2021	after 2021	after 2021
expand Wellesley WS	2021	after 2021	after 2021	after 2021	after 2021	after 2021
expand Wellesley WWTP	? (2005)	2006	2012	2013	2008	2016
N. Hamburg-Baden WS: 1st expansion	1996	1994	1994	1994	1996	1996
N. Hamburg-Baden WS: 2nd expansion	2016	2019	2019	2019	2021	2021
close Baden WWTP, expand NH-B WWTP	? (2003)	2005	after 2021	after 2016	2009	after 2021
expand Ayr WS	2006	2008	2008	2008	2010	2010
expand Ayr WWTP	2009	2011	2020	2018	2015	after 2021

not considered in the WTMP in determining 2021 design wastewater flows because "inflow and infiltration does not appear to be a significant flow contributor to the WWTPs" (WTMP, p.6-11).

Water use efficiency measures are of particular interest in an analysis such as the present one, since they can delay the expansion of both water supplies and WWTPs. The LTWS concluded that only two water use efficiency measures were worth including in forecasting demands for water. These were the plumbing code modification that was to be initiated by the Province of Ontario in January, 1996, and the plumbing fixture replacement program that the Region has already started. The 'integrated scenario' of Table 5.11 already includes the plumbing code change. The scenarios in the last two columns of Table 5.11 also include the fixture replacement program.

Water supply expansion for the Tri-City-Elmira-St. Jacobs area is expected to be needed by 2018 according to the LTWS. In the integrated scenario presented here, expansion is needed at 2013, five years earlier. This is because the integrated scenario does not include fixture replacement. With fixture replacement, however, this analysis gives the year 2020 for the next water supply expansion. This is because not only fixture replacement was included, but also the plumbing code modification, in Elmira and St. Jacobs, whereas the LTWS did not include it. Significant delays in building a new St. Jacobs-Elmira WWTP could be achieved by combining fixture replacement with I/I reduction. Many other significant delays in expansion can be found in Table 5.11. Expansions which are delayed to beyond the end of the planning period are difficult to assess and in the case of the Waterloo and Kitchener WWTPs, where even without implementing fixture replacement or I/I reduction, expansion was not required within the planning period, expansion delays are impossible to quantify.

In order to evaluate the expansion scenarios of Table 5.11 with respect to cost, present values of each were calculated where possible. These are shown in Table 5.12. Present values were calculated in the following way. Capital costs of expansion were obtained from the LTWS (p.4-2, 4-13) and the WTMP (Appendix I). The first water supply expansion for New Hamburg-Baden was to be completed in 1996. This was presumed not to change for any of these scenarios, so that it was not necessary to include the cost of this expansion in comparing scenarios. For the Tri-City-Elmira-St. Jacobs water supply expansion, the groundwater option of the traditional supply strategy was assumed as before (Table 5.11), so that the expansion cost was $61.3 million. Water supply expansions were assumed to occur in a single year. These years are given in Table 5.11. The timing of expansion costs for wastewater treatment was dealt with differently. In the WTMP (Appendix I), all WWTP expansion costs were deemed to be incurred in the years 2001 and 2011, in most cases, 50% of the cost in 2001 and 50% in 2011. In two cases, however, Elmira-St. Jacobs and New Hamburg-Baden, 80% of the cost was deemed to occur in 2001 and 20% in 2011. (In these two cases, the calculations of present value have been done incorrectly in the WTMP, Appendix I. This analysis followed what was said to have been done, since it was impossible to determine how the calculations had in fact been done.) The same 10 year spacing of costs was used in this analysis, but the years were delayed in accordance with the delay to be seen in Table 5.11. For example, the expansion of the Ayr WWTP is forecast to occur in 2009 by the WTMP. The scenario from this analysis with reduction of I/I to 20% shows this expansion to occur in 2018, a delay of nine years. Therefore, the present value of this scenario was assessed with 50% of the expansion cost in the year 2010 and 50% in the year 2020. The inflation rate (2%) and discount rate (6%) were used as those that were used in the WTMP (Appendix I). Costs of I/I reduction programs are not included in Table 5.12.

Costs of fixture replacement programs were determined as follows. The cost of the Tri-City area fixture replacement program was taken from the LTWS (Table 2-18). It amounted to $42 million ($2.8 million per year over 15 years). According to this analysis, the water savings from the Tri-City fixture replacement program amount to 17 thousand

Table 5.12. The present values of expansion costs ($ million) of the scenarios, including cost of fixture replacement programs, but excluding costs of I/I reduction

	reported scenario	integrated scenario	I/I reduced by 50%	I/I reduced to 20%	fixture replacement	I/I to 20%, fixt. replace.
expand Tri-City-Elmira-St. Jacobs WS	$23.43	$28.40	$28.40	$28.40	$21.69	$21.69
new SJ-E WWTP	$28.32	$25.23	$18.55	$20.82	$23.26	$17.17
expand Waterloo WWTP	?	?	?	?	?	?
expand Kitchener WWTP	?	?	?	?	?	?
expand Hespeler WWTP	$0.85	$0.56	<$0.56	<$0.56	<$0.56	<$0.56
expand Galt-Preston WWTP	$10.93	$7.44	<$6.89	<$6.89	<$6.89	<$6.89
Tri-City-Elmira-St. Jacobs fixture replacement	$27.89	$0.00	$0.00	$0.00	$24.60	$24.60
Tri-City-E-St. J total	?	?	?	?	?	?
expand Welles. WWTP	$0.74	$0.71	$0.56	$0.54	$0.66	$0.48
Wellesley fixt. replace.	$0.00	$0.00	$0.00	$0.00	$0.13	$0.12
Wellesley total	$1.35	<$1.32	<$1.17	<$1.15	<$1.40	<$1.21
expand NH-B WWTP	$9.01	$8.34	<$4.51	<$5.46	$7.15	<$4.51
Wilmot fixt. replace.	$0.00	$0.00	$0.00	$0.00	$0.65	$0.53
Wilmot total	$10.08	$9.29	<$5.46	<$6.41	$8.68	<$5.92
expand Ayr WWTP	$0.20	$0.19	$0.13	$0.14	$0.16	<$0.13
Ayr fixt. replace.	$0.00	$0.00	$0.00	$0.00	$0.22	$0.22
Ayr total	$1.29	$1.20	$1.14	$1.15	$1.31	<$1.28

cubic meters per day. Fixture replacement programs for the Townships were priced at the same rate, i.e. $2.47 million per thousand cubic meters per day.

The fixture replacement program recommended in the LTWS would be complete by 2011 (LTWS, Table 2-19), even though the LTWS forecasts that an addition to the water supply would not be needed until 2018. This may reflect a lack of confidence in the effectiveness of the fixture replacement program. However, since the Region reviews water planning approximately every five years, there should be ample opportunity for on-going assessment. A better distribution of costs for this program would be achieved if it were completed by 2018 (or, according to this analysis, 2020), the same year that additional water is needed. The early completion year effectively inflates the cost of the fixture replacement program. This is well illustrated in Table 5.12, where the present value of the LTWS fixture replacement program for the Tri-City area, with a completion year of 2011, is $27.89 million, and the present value of the corresponding program of this analysis, with a completion year of 2020, is only $24.60 million, even though this program also includes Elmira and St. Jacobs. The timing of water efficiency programs should be integrated with the timing of expansions of water supply.

The timing of water use efficiency programs should also be sensitive to expansions of wastewater treatment facilities. The first such forecasted expansion is the construction of a new WWTP at St. Jacobs to service Elmira and St. Jacobs. The Region is currently operating a fixture replacement program in Elmira and St. Jacobs in order to ease the wastewater treatment situation. This program is mentioned in the LTWS, but is not included in its water use forecasts. Water use forecasts for Elmira - St. Jacobs were not developed in the WTMP either, so that the impact of the Region's program there is not reflected in either study. The difference between the Wellesley fixture replacement programs of Table 5.12 in the last two columns is due to different completion years required by WWTP expansion.

Table 5.12 could be used in determining an appropriate level of spending on I/I reduction. For example, looking at wastewater treatment in St. Jacobs and Elmira, the difference between the 'reported' scenario and to 'I/I reduced to 20%' scenario amounts to $7.5 million. Therefore an I/I reduction program with a present value of up to $7.5 million could be undertaken. There would of course be uncertainty about actually achieving the reduction to 20% upon which the $7.5 million value is based. However, it must also be pointed out that the $7.5 million value is an underestimate. This is because it is based on an expansion sized to meet the 2021 design flows forecast in the WTMP. To put it another way, if one did nothing about reducing I/I and expanded the WWTP, one would have a WWTP which would not need expansion until 2021. If an I/I reduction program with a present value of exactly $7.5 million were undertaken, I/I was reduced to exactly 20% of wastewater flows and the WWTP was expanded by the very same capacity increase, one would have a WWTP which would not need expansion until some years after 2021.

The considerations in the previous paragraph point out that the benefits shown in Table 5.12 deriving from delaying expansions are actually underestimated. This is because the various scenarios do not have a common planning end year, or to put it a different way, the size, and therefore the cost, of the expansions should be varied so that a common planning end year of 2021 was fixed for all scenarios. It is impossible to quantitatively assess delays in expansion when no expansions are foreseen within a planning period. Expansion of the Waterloo and Kitchener WWTPs provide a good example. Because the Waterloo and Kitchener WWTPs do not have a projected expansion within the planning period, it is impossible to evaluate the overall benefit of water efficiency programs such as fixture replacement programs.

5.5 Conclusions

Integration of water supply planning and wastewater treatment planning seems to be important for developing a consistent data base. It seems to be crucial when expansions are planned especially when water use efficiency programs are being considered.

The foregoing analysis attempted to go some way towards integrating the two reports, the LTWS and the WTMP, with respect to water use efficiency. The attempt raised questions about differences in unserviced populations with respect to water supply as opposed to wastewater treatment, about how water use projections should be used to help project wastewater flows and about the timing of expansions of water supply systems and wastewater treatment plants. Many of these questions could be resolved by the use of consistent data in both studies. The issue of water use efficiency as it applies to the timing of system expansions, however, is fundamentally different. It is a methodological issue that the best of data cannot change. In both studies there is the recognition that water use efficiency can delay the expansion of both water supply systems and wastewater treatment systems. Neither study makes a quantitative effort to evaluate the effects on wastewater treatment, however.

In the LTWS, the benefit/cost analysis of water prices acknowledges that the effects of delaying the expansion of wastewater facilities were not considered (LTWS, p.5-13). The LTWS does evaluate the effect of efficiency programs on the timing of water supply expansion, but it recommends an efficiency program which does not seem to be timed for maximum benefit in this regard. Thus, even though both water use efficiency and supply management options are dealt with in the same study, these two aspects are not adequately integrated. This raises the issue of how integration can be achieved.

In the Phase 1 Report of the LTWS, supply options are also called 'engineering' options. This by inference labels demand options, which are called 'water efficiency' measures in the Report, as non-engineering. While this labelling may reflect a company bias on the part of consultant, it would seem more appropriate to not refer to 'engineering' options at all since all options are appropriate for the Engineering Department of the Regional Municipality of Waterloo to consider. Considering this and the fact that the WTMP recognized the value of water use efficiency but did include the effects of efficiency in forecasting design flows, the following recommendation is made. Care should be taken to select a consulting consortium which considers water use efficiency to be within its central area of expertise. This might involve having an engineering firm work in collaboration with an environmental consulting firm. While areas of expertise required to do an overall integrative study of supply management, demand management and wastewater treatment may be too diverse to be adequately represented within any one consulting company, the desired balance may be obtained by a collaborative effort.

6

Forecasting Demand and Price with Supply Capacity Expansion

In spite of the relationship between price and demand, the use of price in forecasting water demands has not been a common practice in the past and is still relatively uncommon. For example, a handbook on water rate setting in Ontario (Ontario Municipal Water Association / American Water Works Association, 1979) made no mention of price in forecasting demands. This is also the case in the two latest water supply planning studies in the Regional Municipality of Waterloo (Dillon, 1987; Associated Engineering, 1994). In these, population and/or land area were the only explanatory variables used to forecast water use. Price elasticities of demand are usually assumed, tacitly, to be zero. However, price has been used by municipalities in forecasting water demands, for example, by Weber (1989), and its use is perhaps increasing. An indication of this is that there are now general computer models available for municipal water demand forecasting which incorporates price as an explanatory variable. One such model is IWR-MAIN, developed by the US Army Corps of Engineers (see Opitz et al., 1998). But in this and other examples, price is treated as an exogenous variable.

There is a circular relationship between price and demand. Price should not be treated as an exogenous variable. As Mitchell et al. (1994) say: "a water utility's demands drive its costs; its costs drive its rates; and its rates drive its demands". This relationship has also been described by Howe and Linaweaver (1967) and Prasifka (1988). It would make sense, then, not to treat price as an exogenous variable, but to forecast water demand and price simultaneously.

The importance of doing so is emphasized by a case described by Loudon (1984). In the late 1980s, the water and wastewater utilities of the newly formed Regional Municipality of Durham, Ontario, determined that major expansion was needed in water supply and wastewater treatment facilities to accommodate future development. Accordingly, there was a major construction program in the period 1975 to 1980. In addition, changes were made in the ways most customers paid for water and sewer services: introduction of metering in some areas, the adoption of a 'user pays' philosophy, and the introduction of a sewer surcharge. All these changes led to an effective increase in the marginal price of water faced by customers, which in turn caused a substantial reduction in water use. As a result, the construction of new water supply and wastewater facilities could have been delayed a few years.

Previous work in simultaneously forecasting price and water demand has been done by Hanke (1978) and MacNeill and Tate (1991). Their work differed from mine in several respects. One difference is that they used marginal cost pricing, whereas I used average cost pricing. Another difference is that they dealt with fluctuations in revenue requirements due to supply capacity expansion by spreading out the capital costs of expansion as an annuity over several years. This undoubtedly has the effect of smoothing year-to-year price fluctuations. However, in discussion with Ron Bronson of the Finance Department of the Regional Municipality of Waterloo, I discovered that municipalities also practice a direct form of price smoothing.

This model was set up to represent average cost pricing and to incorporate price smoothing because these are practices in Ontario municipalities. The purpose was to develop an algorithm for price smoothing that anticipates costs. By anticipating costs, customers are paying in advance for some of the future costs of water supply expansion. There is therefore an incentive to reduce demand. Marginal cost pricing of course does this too. My model cannot be considered complete, but my intention was to begin a model which reflects what is done. The model also illustrates the problem that results from not forecasting price and demand simultaneously with respect to untimely capital expansion.

The model developed here only considers water supply, but the principles would be the same if wastewater treatment were involved. In this model, the motivation of price increases comes only from the need to expand the supply system itself, and not from changes in the price structures as in the Durham case. In the Durham case, the Region moved towards a system of lot levy charges as a way of paying for part of the cost of system expansion. The Regional Municipality of Waterloo subsequently has instituted the same type of development charge system. However, in the simulation model, system expansion is paid for only by increasing the price of water. This model could be viewed as a first step towards modelling such a method for paying for expansion. Alternately, development charges could be incorporated into the model at some point. Difficulties in developing the model further in that direction are addressed in Section 6.5.

The model addresses the problem of delaying capacity expansion to avoid over-capacity. Much of the data for this project approximates real data from the Regional Municipality of Waterloo. However, the data are not precise and the forecasts produced cannot be considered to be real forecasts for Waterloo Region. A model of this type could be used by municipalities which are expecting price changes due to water supply expansions, due to demand management programs, or due to wastewater treatment facility expansions or upgrades. Building the simulation model was a sequential process as more and more complexity was added. As an aid to understanding the model, the following description recapitulates this sequential process.

6.1 Forecasting Supply Expansions and Prices

A model was built to forecast supply expansions and prices according to the traditional method. A software application for systems modelling and simulation called STELLA was used for developing this model.[1] It was not necessary to use STELLA, in that there are no explicit differential equations to solve. However, the STELLA diagrams in Figures 6.1a, 6.1b and 6.1c give a clear picture of the process.

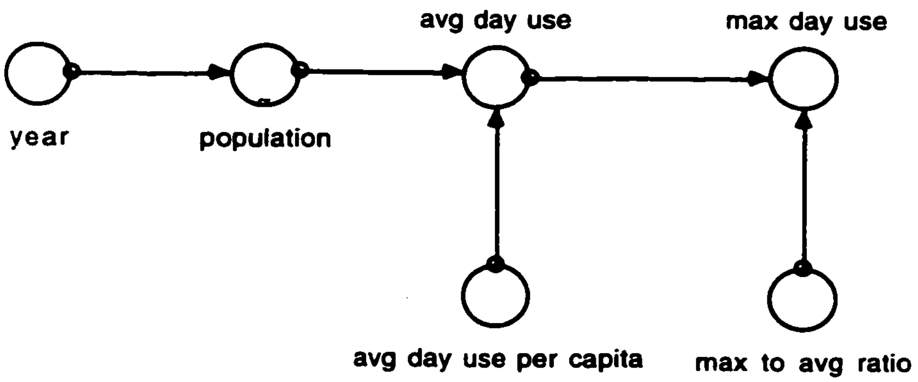

Figure 6.1a. Model 1. Determination of water supply needs.

The traditional method of forecasting water supply needs is to combine a population forecast with an estimate of historical water use per capita. Water use per capita is generally determined by dividing the total water use in a given year by the population. It is thus average day water use, called 'avg day use' in Figure 6.1a. Since peak water use, not average water use, is what provides the motive for supply capacity expansion in many systems, the ratio of annual maximum day water use to annual average day water use is derived from historical data.[2] This is the 'max to avg ratio' in Figure 6.1a. A predicted maximum day use can then be calculated. The traditional method generally assumes constant average day water use per capita and a constant maximum day use to average day use ratio.

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[1] A brief description of STELLA can be found in the Appendix.

[2] The Regional Municipality of Waterloo is unusual in that maximum week water use (expressed per day) is used in place of maximum day water use. Although this reduces the value of the maximum to average ratio, the principles used in developing this simulation model apply equally well to this situation.

The next step is to determine the options for supply expansion. Figure 6.1b shows the section of Model 1 which determines when the next supply expansion is needed. For the purpose of this model, we need not be concerned whether the additional supply is to come from one of the Great Lakes via a pipeline, from groundwater or from surface water. What we need to know is what the step size of the expansion will be. In Figure 6.1b the step size is called 'supply increment.' If maximum day use is greater than supply capacity then 'trigger' will add 1 to the supply stage (step number) and the appropriate supply increment is added to the supply capacity.

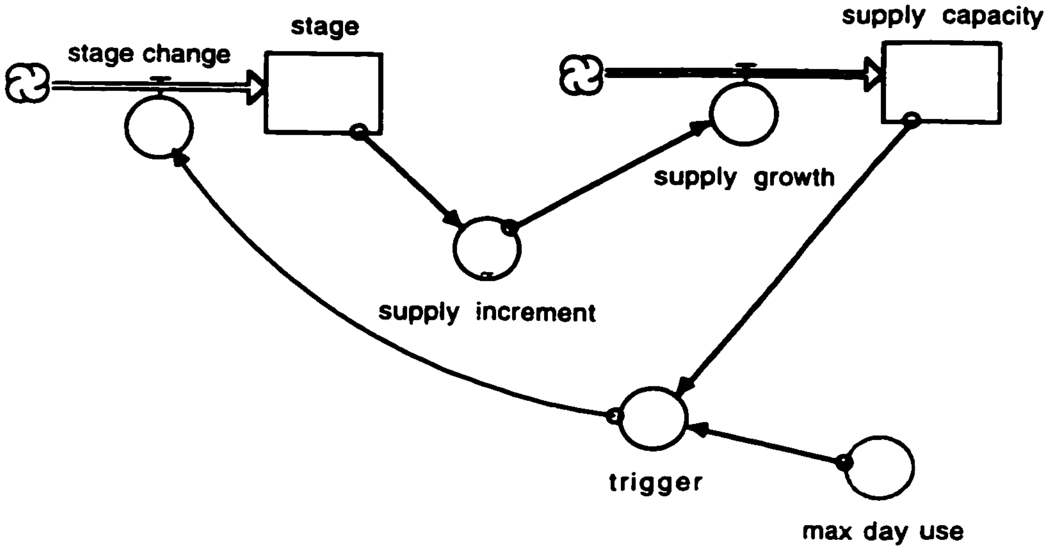


Figure 6.1b. Model 1. Integrating water supply needs with proposed new water supply sources.

Figure 6.1c illustrates the part of Model 1 which deals with costs and prices. In order to set prices, we need to know the capital cost of each expansion and the operating costs associated with each expansion stage. Operating costs are of two types, variable costs and fixed costs. Variable operating costs are for such things as chemicals for water treatment and electricity for pumping. They will vary according to the quantity of water used. Fixed operating costs are for things which are independent of the quantity of water used. Both types of operating costs are expected to change with expansion stage. Prices are set by dividing the total annual cost by the total annual use (average cost pricing).

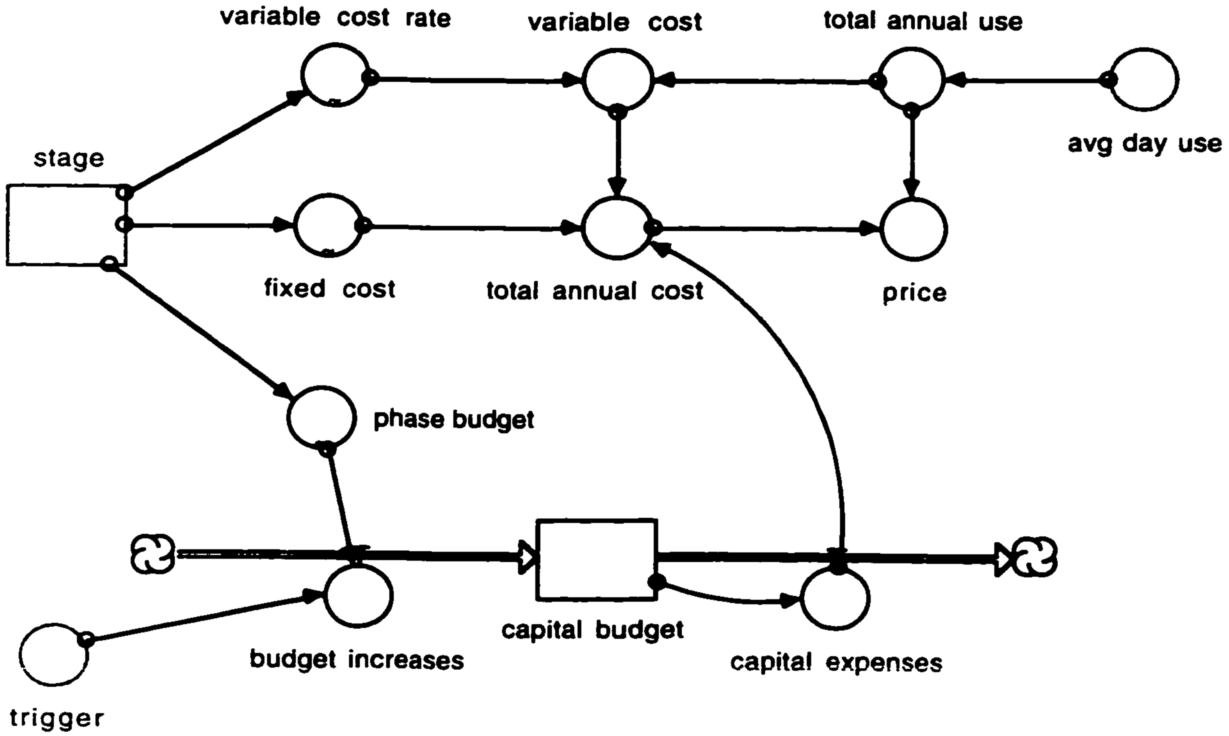


Figure 6.1c. Model 1. Calculating the price per unit of water.

Note that while maximum day use is used to determine the supply expansion timetable, it is total annual use which is used to determine the uniform rate price. The price determined in this way is the average cost price.

Model 1 was run using population and water supply capacity data from the Master Water Supply Study (Dillon, 1987) of the Regional Municipality of Waterloo. Capital and operating costs approximately represent those for Waterloo Region. Model 1 accurately represents the approach taken in and resulting from the Master Water Supply Study except in two important respects. One is a shortcoming of the model itself, i.e. that the 'trigger' operates to add to the water supply only when the maximum day water use already exceeds the supply. To rectify this problem, model output with respect to supply expansion was exported from the STELLA model to a spreadsheet and shifted back one year. Prices were then recalculated in the spreadsheet. The results of this manipulation are shown in Figure 6.2.

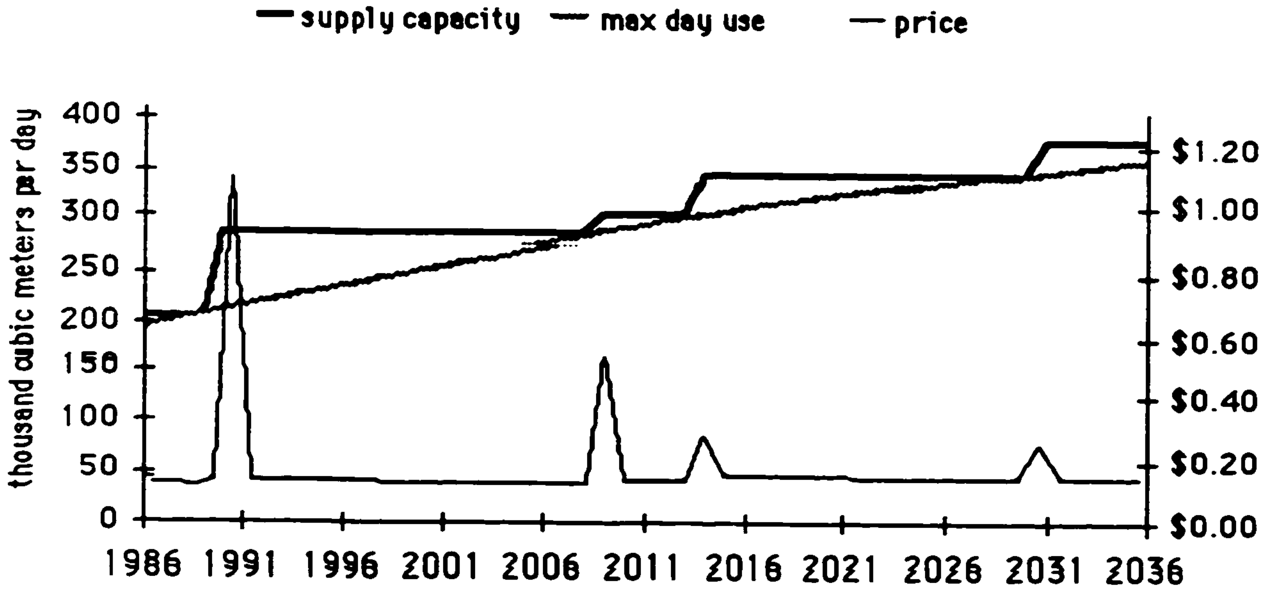


Figure 6.2. Modified output of Model 1, showing supply expansion timetable and prices.

Inspection of Figure 6.2 shows that prices can change drastically from one year to the next. This is the second way in which Model 1 differs from actual practice. In practice, prices are smoothed in order to avoid such extreme price fluctuations.

6.2 Price Smoothing

There is no doubt that price smoothing is practised by municipalities, but there seems to be no standard method. In this analysis, I wished to investigate a methodology for standardizing price smoothing in order to be able to model it and in order to examine the effects of the length of the smoothing period.

It was decided to use a HyperCard stack[1] to calculate the smoothed prices. The stack was set up to run the STELLA model (Model 1). The necessary one year set back of the resultant supply expansion schedule was accomplished with a HyperCard program. Output of Model 1 provided the necessary input for price smoothing.

A good rationale for price smoothing would seem to be that a constant ratio be defined of price change from one year to the next during a smoothing period. In accordance with the principle of revenue neutrality, revenue should balance expenses over the smoothing period. The definitions in Table 6.1 help to clarify this concept of price smoothing.

Table 6.1. Definitions of variables used in price smoothing model.

length of smoothing period in years:	n
price in year prior to smoothing period:	p_0
prices in smoothing period:	$p_1, p_2, p_3, \ldots, p_n$
smoothing ratio:	$r = p_1/p_0 = \ldots = p_n/p_{n-1}$
annual water use in smoothing period:	$U_1, U_2, U_3, \ldots, U_n$
annual revenues in smoothing period:	$p_1U_1, p_2U_2, p_3U_3, \ldots, p_nU_n$
annual variable costs in smoothing period:	$v_1, v_2, v_3, \ldots, v_n$
annual fixed costs in smoothing period:	$F_1, F_2, F_3, \ldots, F_n$
annual capital costs in smoothing period:	$C_1, C_2, C_3, \ldots, C_n$
revenue balance at start of smoothing period:	B_0

---

[1] HyperCard is a software application produced by Apple Computer, Inc. and Claris Corporation. A 'stack' is a HyperCard file.

In terms of these defined symbols, the balance at the end of a smoothing period should be as follows:

$$B_n = p_0 \sum_{i=1}^{n} r^i U_i - \sum_{i=1}^{n} (v_i U_i + F_i + C_i) + B_0 \qquad \text{eq 6.1}$$

The problem then was to solve equation 6.1 for the smoothing ratio, r. In theory, B_n should be set equal to zero. In practice, finding the value of r which yields a B_n exactly equal to zero is unnecessarily precise, especially since the various p_i's were all rounded to the nearest 0.1¢ per thousand gallons. The values of U_i, v_i, F_i, and C_i obtained from Model 1, were assumed to be constant at this stage of model building. The values of p_0 and B_n for the first smoothing period were input directly to the HyperCard stack. An iterative trial and error program was written in the HyperTalk language to solve equation 6.1 for r. Solutions for equation 6.1 have to be found for successive smoothing periods. For example, if the length of smoothing period is five years, then the first smoothing period would run from year 1 to year 5 inclusive, the second smoothing period would run from year 2 to year 6, and so on. The last smoothing period would be the last five years of the simulation period. Figure 6.3 shows the results obtained from smoothing the prices of Figure 6.2.

6.3 Price Elasticities

None of the modelling described up to this point has addressed the issue of the effect of price on demand for water. Typically price elasticity of demand is a function of price. However, elasticities are often practically constant over small price changes. In the case of water, different elasticities apply to different end uses of water.

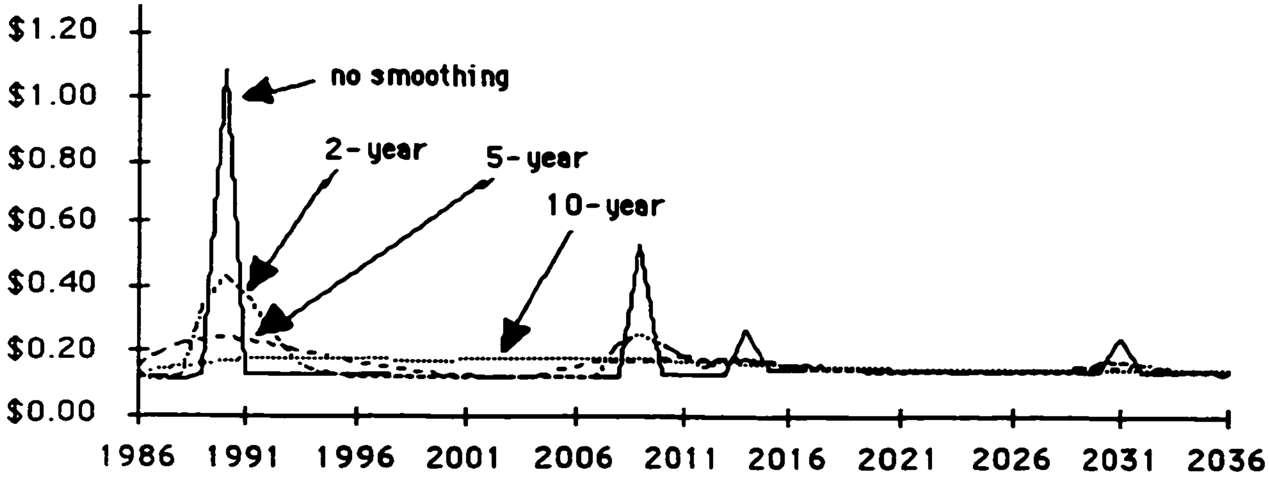


Figure 6.3. Price smoothing for various lengths of smoothing period. Prices are in dollars per cubic meter.

It was decided to segregate daily per capita water use into seasonal components plus a maximum day water use. This was done so that a different price elasticity could be applied to each component. STELLA Model 1 was modified to do this, producing STELLA Model 2. The HyperCard stack was rewritten so that the price smoothing operation could be run on output from Model 2. The differences between Model 1 and Model 2 are in the determination of water supply needs. This section of Model 2 in shown in Figure 6.4. The corresponding section of Model 1 is shown in Figure 6.1a.

In order to explain the segregation of daily per capita water use, it is helpful to consider the actual numbers that were used initially, i.e. in the absence of price elasticity. A year-round water use component, called base water use per capita ('base_day_use_rate' in Figure 6.4) was set at 95 gal/person/day. A summer additional water use ('sumr_exces_use_rate' in Figure 6.4), used during the four summer months in addition to base use, was set at 10 gal/person/day. A maximum day excess use ('max_excess_use_rate') was set at 42 gal/person/day. A price elasticity of -0.05 was used for base use, -0.4 for summer excess use and -0.9 for maximum day excess use.

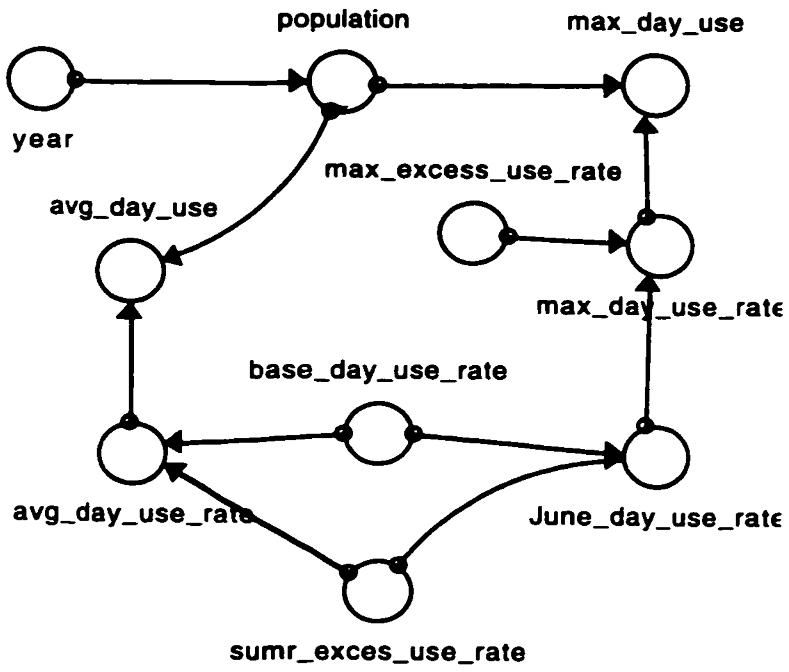


Figure 6.4. Model 2. Determination of water supply needs with segregation of water use into base, summer and maximum day components.

These three components were used as follows in Model 2. The annual daily water use per capita was calculated by adding the base component to one third of the summer excess component, since the summer excess component is used in one third of the months of the year. The distribution of summer water use was not even over the four summer months. June average day per capita use was calculated as the base component plus 1.33 times the summer use component. The June average day per capita use was then added to the maximum day excess component to yield the maximum day per capita use. All the values used in the simulation model for calculating water use approximate historical data from the Cambridge-Kitchener-Waterloo area of the Waterloo Region.

Model 2 is used as follows. From the HyperCard stack, Model 2 is now used in place of Model 1 to obtain a supply expansion schedule. It is convenient to have to use only one STELLA model. The expansion schedule, consisting of a list, by year, of variable operating cost, fixed operating cost, capital expense, total annual water use and supply capacity, is recorded on a card in the HyperCard stack for future use. The schedule is then used as input for price smoothing. Recall that the price smoothing program assumed that water use per capita remained constant. This set of smoothed prices therefore represent the case of no elasticity (see Figure 6.5). The three water use components are then adjusted for elasticity and Model 2 is run again to find the total annual water use for each forecast year. This information is used with the saved expansion schedule for a second round of price smoothing. This process is repeated until price smoothing yields the same set of prices on two consecutive iterations. Figure 6.5 shows the first and last iterations of this process for 5-year price smoothing.

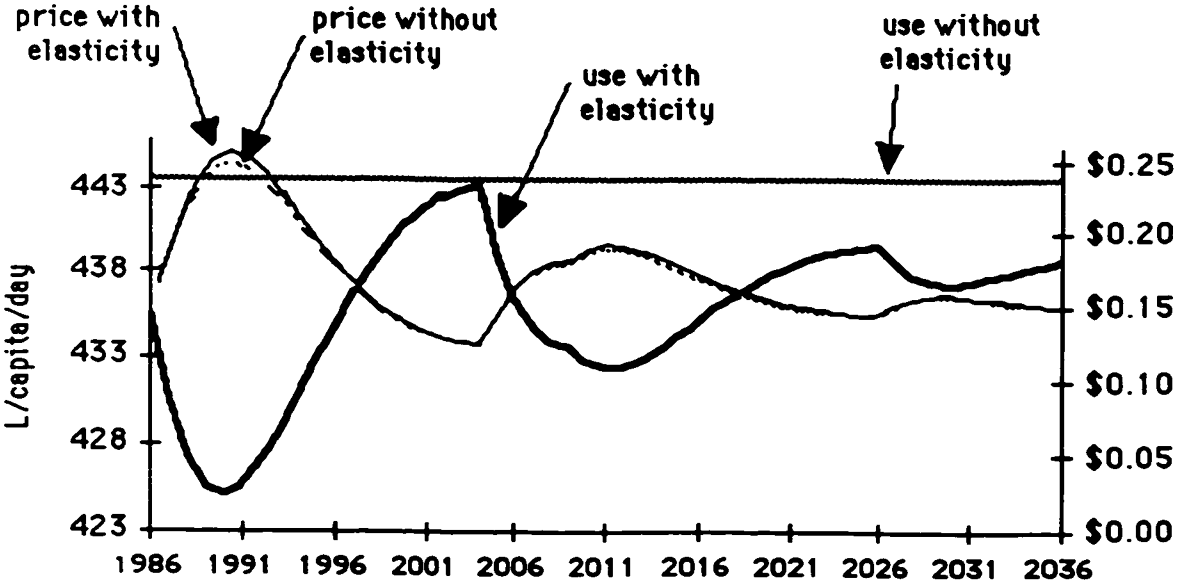


Figure 6.5. The effect of price (per cubic meter) on average day water use per capita and vice versa with 5-year price smoothing.

6.4 Resultant Scenarios for Scheduling Expansions

The outcome of the simulation described up to this point, in terms of supply capacity, maximum day use and price, is presented in Figure 6.6. It can be seen from Figure 6.6 that the supply capacity expansions, which are identical to those of Figure 6.2, come sooner than is really needed. This is precisely the problem noted with respect to overcapacity in the Regional Municipality of Durham. The modelling up to this point has succeeded in qualitatively reproducing this phenomenon.

To proceed beyond this and create a simulation model which can be used to reduce overcapacity, it is necessary to find some appropriate way of altering the expansion schedule. The greater the number of steps (events) in a possible expansion schedule, the more choices there are. Iteration through all possible expansion scenarios would be very inefficient.

It was decided to proceed in an iterative fashion, but to try to use the information in one expansion scenario as an aid to creating the next. For example, if Figure 6.6 represents Scenario 1, then we could use the information on maximum day use to create a new expansion schedule. Running the new expansion through successive iterations of price smoothing and adjustment for elasticity would yield Scenario 2. Scenario 2 is presented in Figure 6.7.

Using the maximum day use figures from Scenario 2, Scenario 3 was created. This is presented in Figure 6.8. Scenario 3 differs only slightly from Scenario 2. An attempt to create a Scenario 4 failed, since the result was identical in every way to Scenario 3.

Within the HyperCard stack, a program was written to iteratively create the scenarios. The program exits from iteration when a scenario is created which has already appeared. Certain key information is recorded from each scenario in order to allow recognition of a previously occurring scenario. This information is also use in evaluating the scenarios.

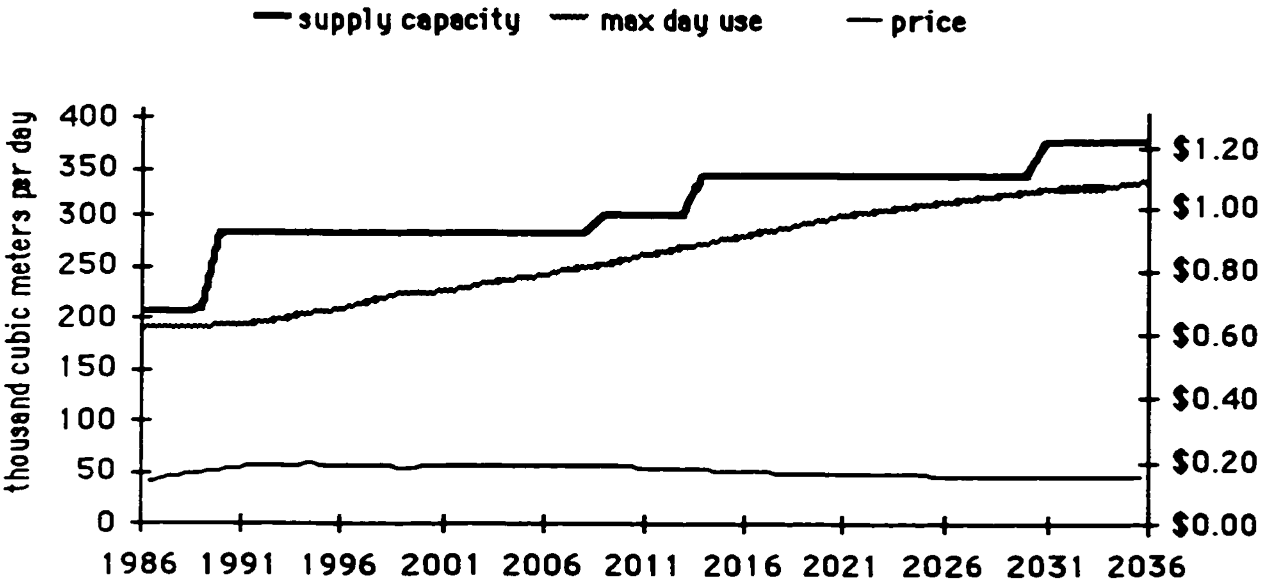


Figure 6.6. Water supply expansion and prices, 10 year smoothing, Scenario 1.

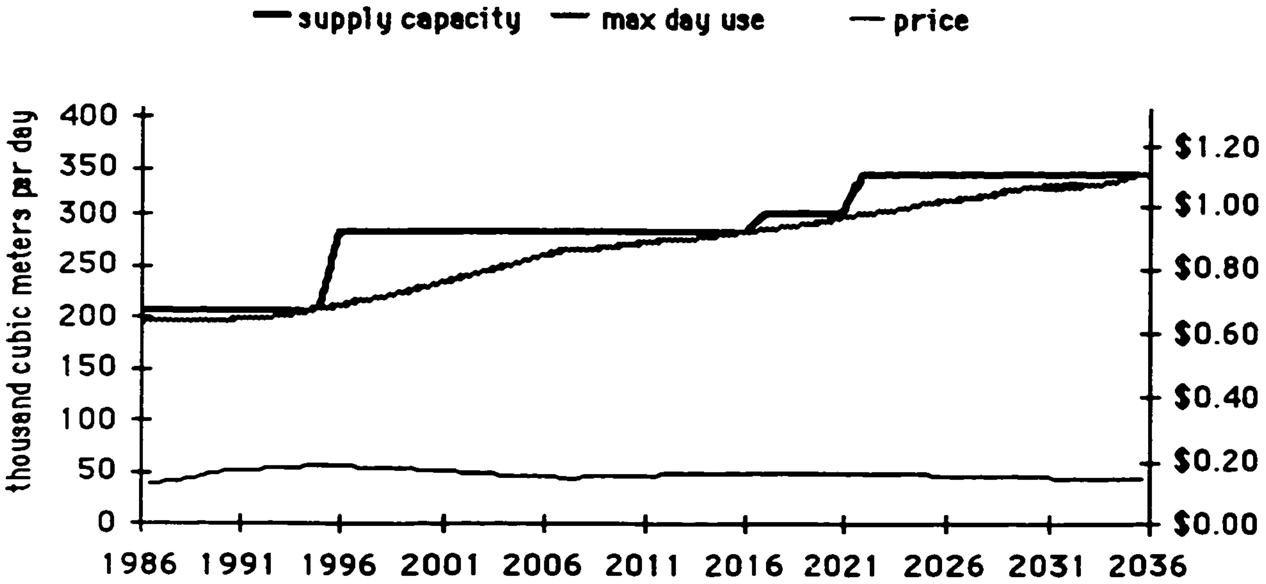


Figure 6.7. Water supply expansion and prices, 10 year smoothing, Scenario 2.

An important point to be made about these scenarios is that each one represents one version of the future. Each one is equally valid in its agreement with the view of reality upon which this model has been built, although some may have unacceptable characteristics. Perhaps other solutions are obtainable using a different search algorithm.

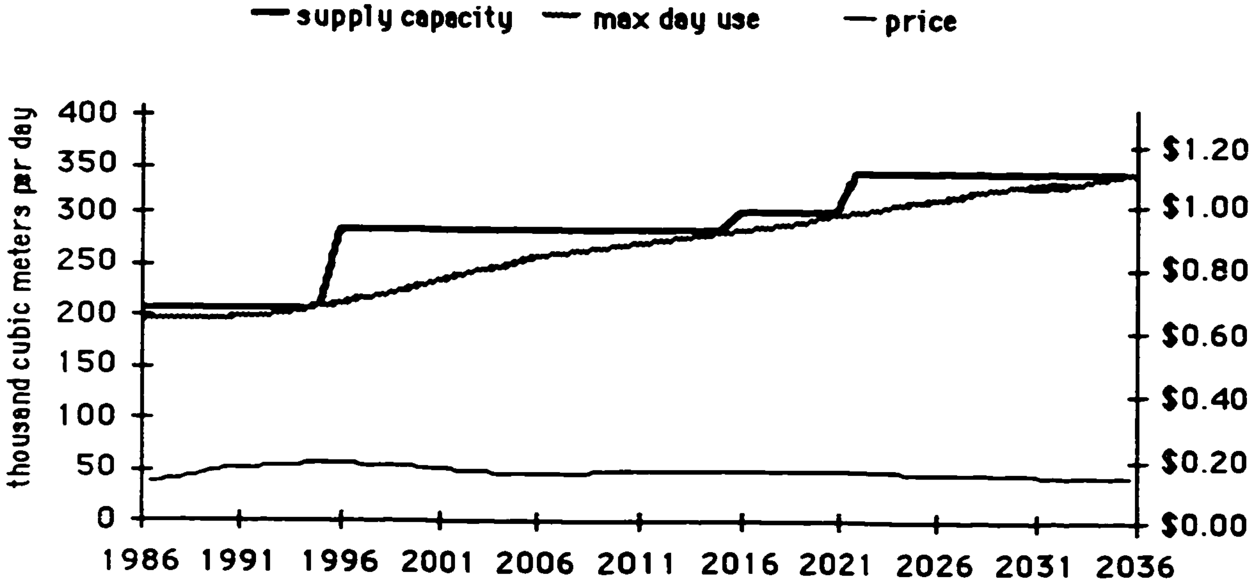


Figure 6.8. Water supply expansion and prices, 10 year smoothing, scenario 3.

A water utilities manager, then, would be able to choose from among the scenarios based on considerations of policy. Which ones fail to meet water supply demands? Which ones are good at delaying capital expenditure? Do any contribute to water conservation? The HyperCard program saves information about each scenario that it creates. This information can be used to help evaluate scenarios in order to make policy decisions.

For each scenario, the following evaluation criteria are recorded: the maximum price increase from one year to the next; the present value of capital expansion based on the starting year of the scenario; the average day water use for the last year of the scenario, the minimum value by which capacity exceeds maximum day use; and the average price per unit volume of water for the entire simulation period. All scenarios had the same starting year and the stopping year. Table 6.2 shows the evaluation criteria saved for two simulation runs, a 5-year price smoothing run and a 10-year price smoothing run. A discount rate of 5% was used in the HyperCard program to calculate present values. Out of eight created scenarios, these two simulation runs yield only three scenarios for which supply capacity exceeds maximum day use in every year. Of these three, the best price smoothing is obtained with Scenario 1 (10-year), with a maximum price increase of 9%. The best scenario for delaying capital expenditure is Scenario 3 (10-year) with a present value of $36 million. There is no difference among the scenarios for water conservation, all three having the same average day water use by the last year of forecasting. Scenario 3 (10-year) has the lowest average price per unit volume of water.

Table 6.2. Evaluation of model output for 5-year price smoothing and 10-year price smoothing. Scenarios in which supply meets demand are in bold faced type.

Length of Smoothing Period	Scenario	Maximum Price Increase (%)	Present Value of Expansion ($ mill.)	Average Day Water Use (10^3 m^3)	Minimum Capacity Exceedance (10^3 m^3)	Average Price (¢/m^3)
5-year	**1**	**23**	**50**	**232**	**16.8**	**16.7**
	2	33	36	232	-16.4	15.8
	3	24	51	227	-7.7	16.4
	4	33	35	232	-18.6	15.9
	5	24	50	232	-4.1	16.1
	6 (= 4)	33	35	232	-18.6	15.9
10-year	**1**	**9**	**50**	**232**	**14.5**	16.7
	2	10	36	232	-0.9	15.7
	3	**10**	**36**	**232**	**0.5**	15.8
	4 (= 3)	10	36	232	0.5	15.8

6.5 Summary and Conclusions

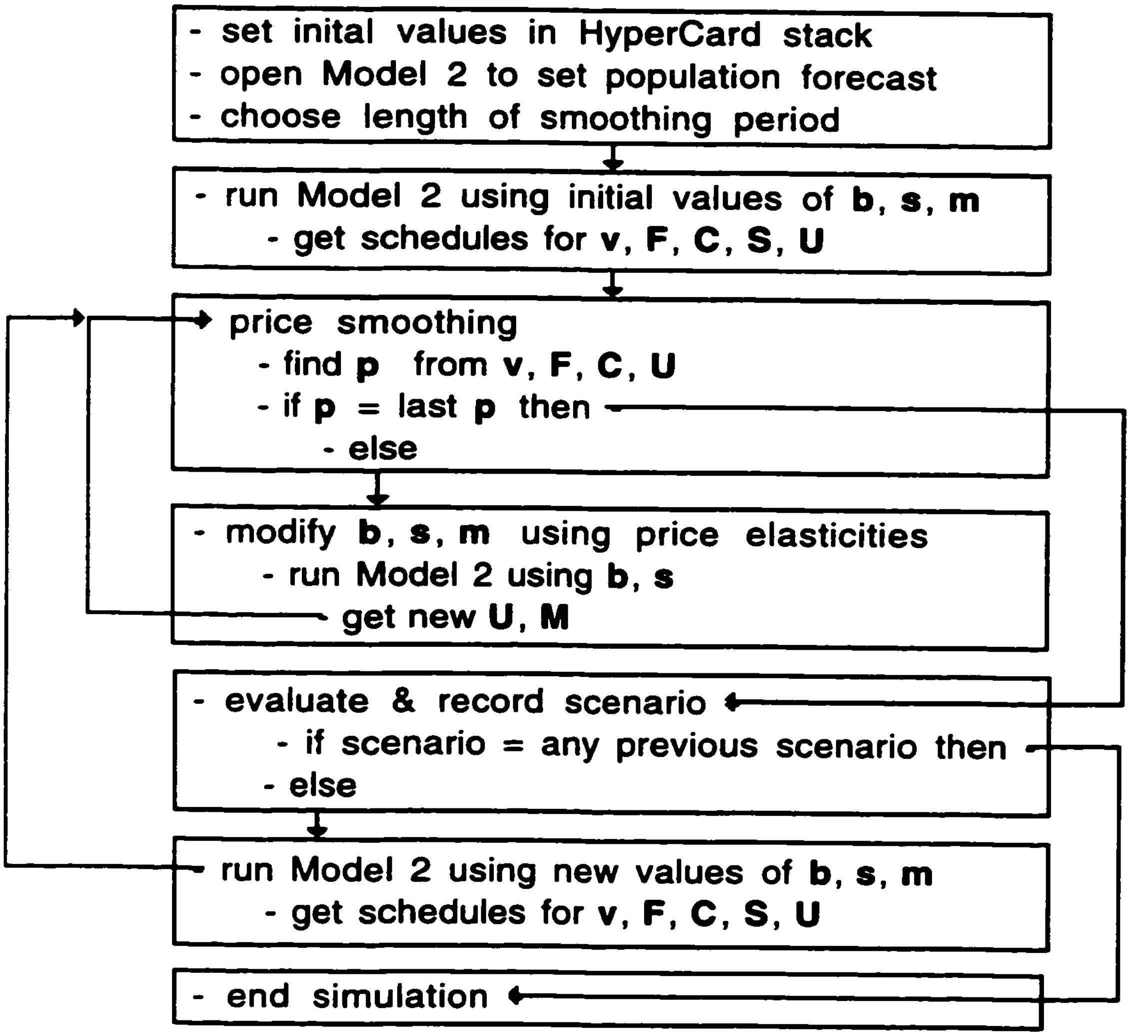
The various parts of the simulation model so far have been presented piecemeal in the order in which they were developed. An overall summary of the model is presented in Figure 6.9.

After the initial set-up of the model, the model runs automatically until it has created all the expansion scenarios that it can. The model saves selected evaluation criteria and a list of expansion stage change years for each scenario. A full record of the scenario remains in the stack only for the last scenario created. It is also possible to limit the number of scenarios. This is useful if complete scenario output is desired for any but the last scenario.

This simulation model was successful in showing that anticipatory price smoothing tends to reduce demand. The model also predicted qualitatively the type of overcapacity problem encountered when price elasticity of demand is not integrated with water supply planning.

It was necessary to deal with and standardize a version of price smoothing in order to accomplish these goals. Other versions of price smoothing are possible and might be worth investigating.

The are many ways in which this model could be improved. One might be to increase the segregation of water use so that different price elasticities could be applied to, for example, industrial use (by industry class), residential use and commercial use. There is a practical difficulty and a pitfall associated with this approach. The practical difficulty is that it is not easy to get data for this. The pitfall is that one could spend a lot of time elaborating this kind of model to no purpose unless the virtually impossible task of predicting economic changes within a city were solved. However, in the short term, changes in industry class and commercial type might remain quite constant. Also the elasticities used



b, daily base use per capita
m, maximum day excess use per capita
v, variable operating cost (per unit of water)
C, annual capital expense
M, maximum day water us

s, daily summer excess use per capita
p, price per unit volume of water
F, annual fixed operating cost
U, total annual water use
S, supply capacity

Figure 6.9. Schematic summary diagram of the simulation model.

in this model so far are from literature studies (Prasifka, 1988). Elasticities calculated from local historical water use and prices would be more appropriate.

Price smoothing introduces a problem which this simulation model did not deal with. Because with price smoothing, revenue is not likely to balance expenses in any given year, borrowing costs will be introduced in many years of the simulation. In other years there will be surplus revenue. In practice, many utilities accommodate this with a rate stabilization fund.

Application of this model to the Regional Municipality of Waterloo would bring up another problem. In the Regional Municipality of Waterloo, the Region is the supplier of water. It sells water to the local municipalities at a wholesale price. The local municipalities sell water to consumers at a retail price. The retail prices are what consumers experience. Price elasticities should be based on retail prices. In this model, the costs considered were those to the Region. Costs to the local municipalities, including the costs associated with expanding the water distribution system, should be incorporated into the model. This model could readily be integrated with a similar model incorporating upgrading and capacity expansion of wastewater treatment.

7

Design of Summer Use Pricing

Various water pricing schemes can be used to promote water use efficiency and/or to reduce the ratio of summer peak water use to winter water use. In summer use pricing, the aim is to charge a higher price for sumer water use, that is, for types of water use which are specific to the summer period, when demand for water is highest. Other types of water use are charged at a lower rate, even in summer. Summer use pricing is advocated by some because of its capability for reduction of peak demand. It is also argued that it is those with high summer use contribute more to peak demand than other water customers. These customers contribute more towards the need for capital expansion and its associated costs. Therefore, summer use pricing is also advocated as a means of providing equity in allocating the costs of system expansion. This price structure has been described by Griffith (1977) who called it an 'excess use charge'.

There is a potential problem in the implementation of this pricing structure. There is the possibility that an astute water customer might waste water during the winter period in order to avoid reducing his summer water use or paying for water at the higher price in the summer. Certain customers, depending on their seasonal pattern of water use, may find it feasible to lower their annual water bill by this means. The purpose of this chapter is to analyze the potential problem with a summer pricing charge and to examine ways to minimize it through various design features of the structure that are amenable to adjustment. A similar analysis was presented in Creese and Robinson (1996a).

The summer use price structure has some similarity to an increasing block structure. There is one price for the first block, called the base water use, and a higher price for the second block, the summer water use. In the increasing block structure, the shift in price occurs at the same quantity for all customers. An example was shown in Chapter 2, Figure

2.5, where the shift occurs at a quantity of 100. However, with the summer use price structure, there are two differences. First, the shift from the lower block to the upper occurs at a different quantity for each customer. It is an individualized increasing block structure. The quantity where the shift occurs is determined by the customer's winter water use (also called base use). Customers whose summer water use is not substantially greater than their winter water use do not reach the second block. They are always charged for water at the lower price. Secondly, the second block may only apply in the season of peak demand for the utility.

It is difficult to generalize the responses of customers to this price structure. For this reason, this price structure was not used in this study in any modelling for forecasting of demands for water and for wastewater treatment service. Successful modelling of a large number of individual cases, i.e. the set of customers within a city, requires either the grouping of individual cases into similar classes or the acceptance of a large degree of uncertainty in modelling results. How customers would respond to a summer use price would depend not only on the seasonal pattern of use, where pattern refers only to water quantity, but also on the actual uses of water in different seasons. This is because the effect of price on water use depends on the type of use, not just on the quantity used. A water utility intending to employ this price structure could introduce the price differential gradually over a number of years in order to gain information on its effect on water use empirically. Alternatively, the utility could empirically set prices iteratively, starting with an estimate of effect and adapting as experience is gained in predicting average revenues. Either approach would be essentially an experimental, adaptive way to finding appropriate levels for base use and summer use prices.

7.1 The Wastage Problem

An example of summer use pricing in practice was described by Griffith (1977). In this case, billing was quarterly. The water use of each customer in the winter quarter was defined as the base water use. Water use in any of the other three quarters in excess of 1.3 times the base water use was called 'excess use', but only excess use in either of the two summer quarters was charged at the excess use price. All other water use was charge at the base use price. In Griffith's case, the primary motivation for instituting this pricing system was equity. The need for expansion of a water supply system is governed by its peak use. It is those water users who contribute most to the peak demand who are most responsible for the increased costs associated with system growth. It was argued they should therefore pay more than those who contribute little or not at all to the system's peak use. There was the recognition that water use may be influenced by this pricing system in the direction of lowering system peak use, but this was not the main motivation. Griffith's 'excess use' is called 'summer use' in the present analysis to avoid placing any subjective value on high summer use.

One objection which is frequently raised to such a system is that a customer who uses a great deal more water in the summer than in the winter may be tempted to adjust his base water use upward by deliberately wasting water in the winter. Instead of reducing summer peak water use, such a customer could continue with high summer water use and be charged for it at the base use price. The decision to waste water rests with the customer, but several management parameters impact the decision. In order to design prices to minimize any such action, it is important to understand the circumstances in which wasting water would be advantageous to the customer.

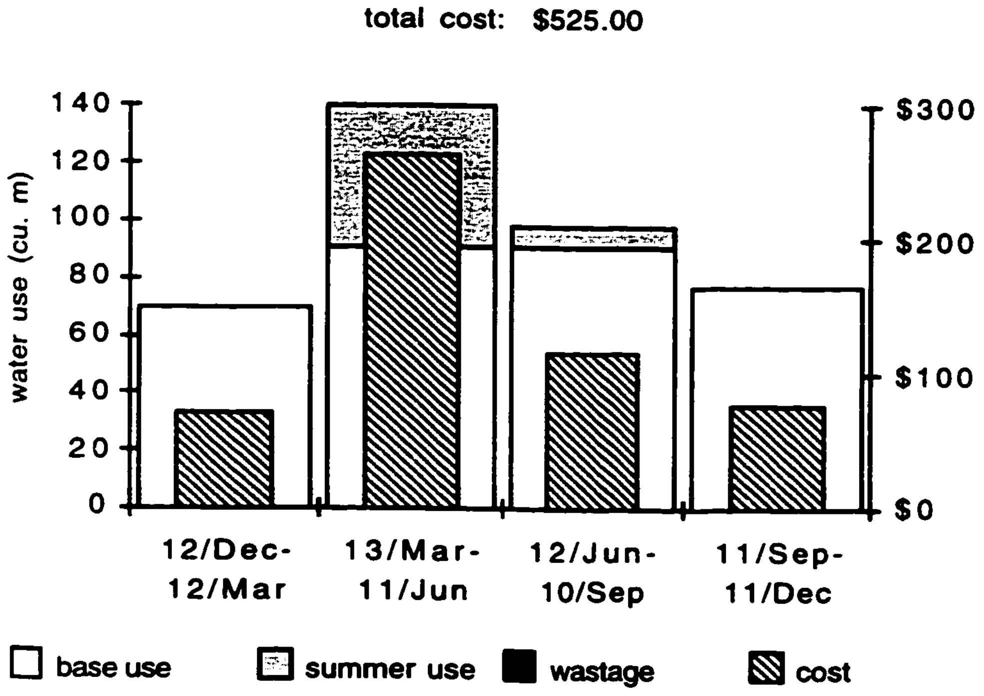


Figure 7.1. An illustrative example of quarterly water use and cost to a customer with a summer use price structure.

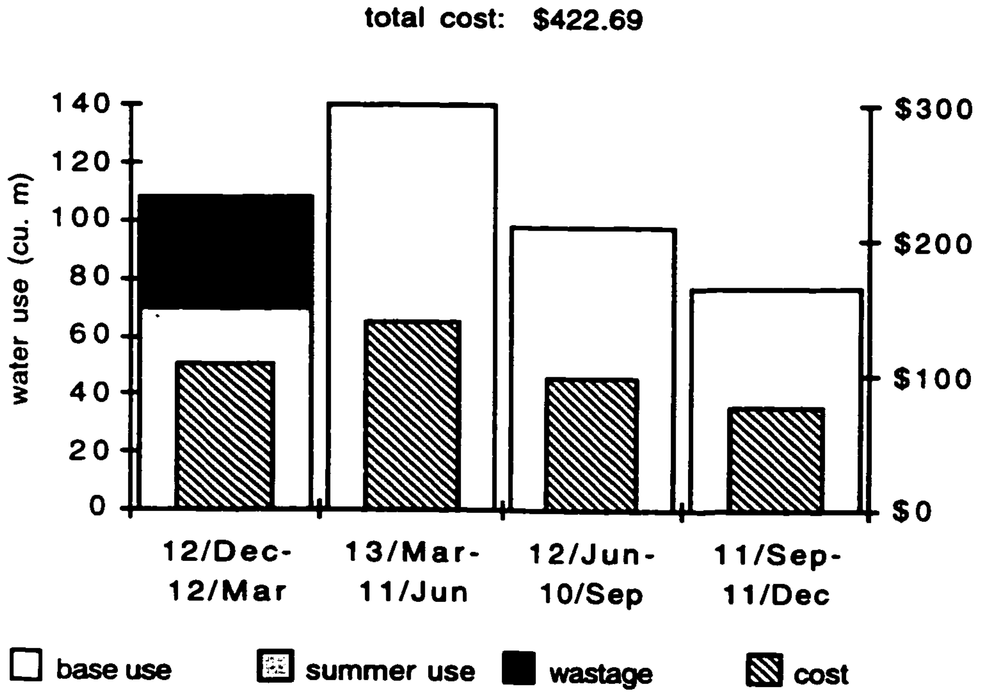


Figure 7.2. The illustrative example continued, now with deliberate wasting.

An illustrative example which should make clear how this system works is shown in Figure 7.1. In this example, as in Griffith's case, billing is quarterly and summer use is defined as 1.3 times the winter quarter water use. The base use charge is \$1.00 per cubic meter, and the effective summer use charge is \$3.50 per cubic meter. In the example, summer use occurs, and is charged as such, in the two summer quarters. If high use had occurred in the billing period which was neither the winter quarter nor one of the two summer quarters, it would have been charged at the base use price. The total charge to the customer for the year is \$525.00.

The customer of Figure 7.1 could waste water deliberately in the winter quarter in order to reduce the quantity of water in the summer quarters paid for at the summer use price. It would take very little trial-and-error work on the part of the customer to discover that increasing the wastage in the winter quarter to just reach the point where a summer use charge was no longer applicable would give the maximum reduction in total annual water bill. This case is shown in Figure 7.2. For this particular customer, wastage in the winter quarter would lead to a 19% reduction in the annual water bill, a 10% increase in annual water consumption, and no change in summer water use. This is not a desirable situation from the demand management point of view.

7.2 Analysis of the Wastage Problem

The water use pattern of the customer is crucial to making this type of response a possibility. Several factors under managerial control can also affect the likelihood of this kind of behaviour. The two most important are:

- **k** the price ratio between the summer use price and the base use price
- r_c the critical ratio which defines what summer use is in relation to base use

The frequency of billing, the number of billing periods which are used to set base use, and the number of billing periods in which the summer use price may be charged are other relevant factors.

The two prices are:

- **p_b** base use price
- **p_s** summer use price, $p_s = k\, p_b$.

Water use can be represented as follows:

- **U_b** base use, i.e. water use in the base billing period if there is only one base billing period, or average water use per base billing period if there is more than one base billing period. The base use is defined not to include deliberate wastage. The number of base billing periods is **n_b**.
- **U_{si}** water use in a non-base billing period in which there is 'summer water use,' i.e. in which water use exceeds the critical ratio times the base use, r_cU_b, provided that the billing period is in the 'summer' category. The subscript, i, runs from 1 to **n_s**, the number of non-base billing periods in which there is 'summer water use.' N.B. It is necessary to order the U_{si} by increasing magnitude, so that as base period wastage is increased, U_{s1} drops out first, then U_{s2}, etc.
- **U_{oj}** water use in a non-base billing period in which there is no 'summer water use.' The subscript, j, runs from 1 to **n_o**, the number of non-base billing periods in which there is no 'summer water use.'

The total water use for the year is:

$$n_bU_b + \sum_{i=1}^{n_s} U_{si} + \sum_{j=1}^{n_o} U_{oj}$$

So that the various water use terms can all be expressed in relation to the base use, the following ratios are defined:

- r_{si} ratios of water use in non-base periods with 'summer use,' to the base use
- r_{oj} ratios of water use in non-base periods without 'summer use,' to the base use

The total water use for the year expressed with these ratios and the base use is:

$$\left(n_b + \sum_{i=1}^{n_s} r_{si} + \sum_{j=1}^{n_o} r_{oj}\right) U_b$$

Water use above $r_c U_b$ in a summer billing period is charged at the summer use price. There is summer use in a summer billing period if $U_{si} > r_c U_b$, i.e. if $r_{si} > r_c$. Table 7.1 illustrates the case of quarterly billing with one base quarter and two summer quarters, both with summer water use.

Table 7.1. Base and summer water use and charges for quarterly billing with one base quarter and two quarters with summer use, with no deliberate wastage.

Quarter	Water Use	Base Use	Summer Use	Charge
base	U_b	U_b	0	$p_b U_b$
1st summer	$r_{s1} U_b$	$r_c U_b$	$(r_{s1} - r_c) U_b$	$(k\, r_{s1} - r_c)\, p_b U_b$
2nd summer	$r_{s2} U_b$	$r_c U_b$	$(r_{s2} - r_c) U_b$	$(k\, r_{s2} - r_c)\, p_b U_b$
other	$r_{o1} U_b$	$r_{o1} U_b$	0	$r_{o1} p_b U_b$

The total annual charge for the case of Table 7.1 (quarterly billing with a charge for summer water use in two peak billing periods) is:

$$T = ((1 + r_{o1} + 2r_c) + k\,(r_{s1} + r_{s2} - 2r_c))\, p_b U_b \qquad \text{eq. 7.1}$$

Equation 7.1 applies to the example of Figure 7.1.

If there is deliberate water wastage in the base period, then the base period water usage will be wU_b, where w is the 'wastage ratio.'

- w ratio of base period water use with deliberate wastage to normal base period water use. The wastage ratio is subject to the constraint, $w \geq 1$. When $w = 1$, there is no wastage.

Table 7.2 shows the same quarterly billing case of quarterly billing as Table 7.1, but with deliberate water wastage in the base quarter. Note that there is still water use charged at the summer use price in both summer quarters. The wastage has not been increased to the point of eliminating this.

Table 7.2. Base and summer water use and charges for quarterly billing with one base quarter and two quarters with summer use, with deliberate wastage in the base quarter.

Quarter	Water Use	Base Use	Summer Use	Charge
base	wU_b	wU_b	0	wp_bU_b
1st summer	$r_{s1}U_b$	wr_cU_b	$(r_{s1} - wr_c)\, U_b$	$(k\, r_{s1} - wr_c)\, p_bU_b$
2nd summer	$r_{s2}U_b$	wr_cU_b	$(r_{s2} - wr_c)\, U_b$	$(k\, r_{s2} - wr_c)\, p_bU_b$
other	$r_{o1}U_b$	$r_{o1}U_b$	0	$r_{o1}p_bU_b$

With base quarter wastage, equation 7.1 changes to:

$$T(w) = ((w + r_{o1} + 2wr_c) + k\,(r_{s1} + r_{s2} - 2wr_c))\, p_bU_b \qquad \text{eq. 7.2}$$

It can be similarly shown that in the case of quarterly billing where there is summer use in only one summer quarter that the total annual charge is:

$$T(w) = ((w + r_{o1} + r_{02} + wr_c) + k(r_{s1} - wr_c))\, p_bU_b \qquad \text{eq. 7.3}$$

Equation 7.2 and equation 7.3 can be generalized to:

$$T(w) = \left(\left(w + \sum_{j=1}^{n_o} r_{oj} + n_s w r_c\right) + k\,\left(\sum_{i=1}^{n_s} r_{si} - n_s w r_c\right)\right) p_bU_b \qquad \text{eq. 7.4}$$

The functional dependence of the total annual charge, T(w) on w is not limited to the explicit dependence shown in equation 7.4. There is an implicit dependence, in that n_s and n_o are dependent on w, since the higher the value of w, the fewer the number of billing periods which incur an summer use charge. This results in T(w) being a continuous function with a discontinuous slope. The case of the customer of Figure 7.1 and Figure 7.2 is shown in Figure 7.3. In this example, the curve has three segments, each with a different slope. The first segment represents T(w) when there are two billing periods with chargeable summer use. It runs from w = 1 (no wastage) to $w = r_{s1}/r_c$. At $w = r_{s1}/r_c$ one summer billing period drops out, and equations 7.2 and 7.3 are equally valid. The second line segment goes from $w = r_{s1}/r_c$ to $w = r_{s2}/r_c$. At $w = r_{s2}/r_c$, the remaining summer use billing is eliminated. In the region where $w \geq r_{s2}/r_c$, the cost to the customer increases as w increases.

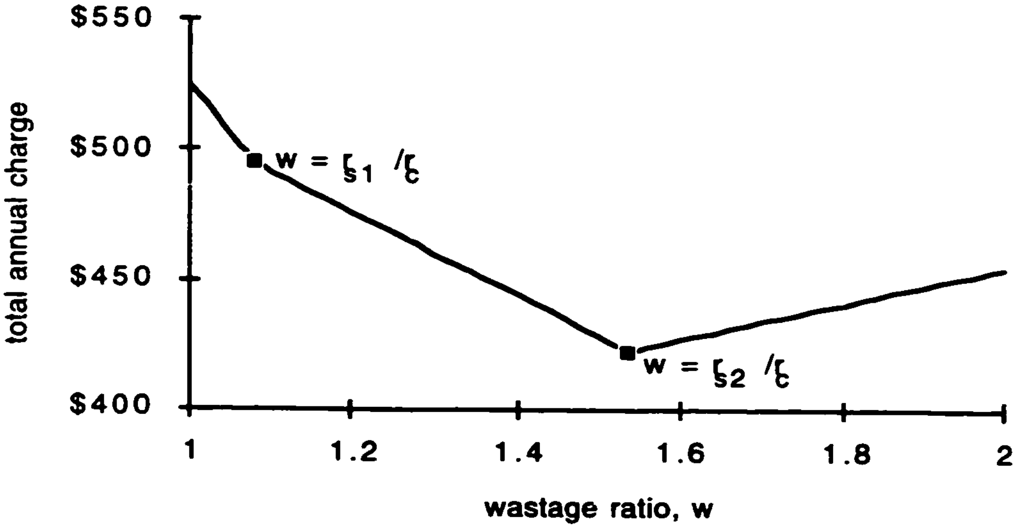


Figure 7.3. Example of total annual charge for water as a function of deliberate wastage.

Equation 7.4 was derived for quarterly billing, but it can equally well apply to other billing schemes with one base period. Generalizing further to more than one base period by including n_b:

$$T(w) = \left(\left(n_b w + \sum_{j=1}^{n_o} r_{oj} + n_s w r_c\right) + k \left(\sum_{i=1}^{n_s} r_{si} - n_s w r_c\right)\right) p_b U_b \qquad \text{eq. 7.5}$$

The function in equation 7.5 will have decreasing slope, indicating that the total annual charge can be reduced by means of increasing the base period wastage, if:

$$\frac{dT}{dw} < 0, \text{ where } \frac{dT}{dw} = (n_b + n_s r_c - k n_s r_c)\, p_b U_b$$

Hence, if the following condition is true, it will not be possible to save money with a summer use price structure by deliberately wasting water in winter:

$$k < 1 + \frac{n_b}{n_s r_c} \qquad \text{eq. 7.6}$$

The most likely value of n_s is zero, in which case there is no summer use charge for that customer and k can be infinite. However, of those customers who are charged for summer use, the most common case will be a charge in one billing period only, i.e. $n_s = 1$. Figure 7.4 shows examples of equation 7.6 with $n_s = 1$ for three different billing schemes, as follows:

(1) monthly, six base periods ($n_b = 6$)

(2) bimonthly, two base periods ($n_b = 2$)

(3) quarterly, one base period ($n_b = 1$)

It should be noted that an individual customers who has $n_s > 1$ may have more impact on peak water system demand than one who has $n_s = 1$, provided that any additional billing period in which there is some summer use charge coincides with the peak day or peak week of the water system.

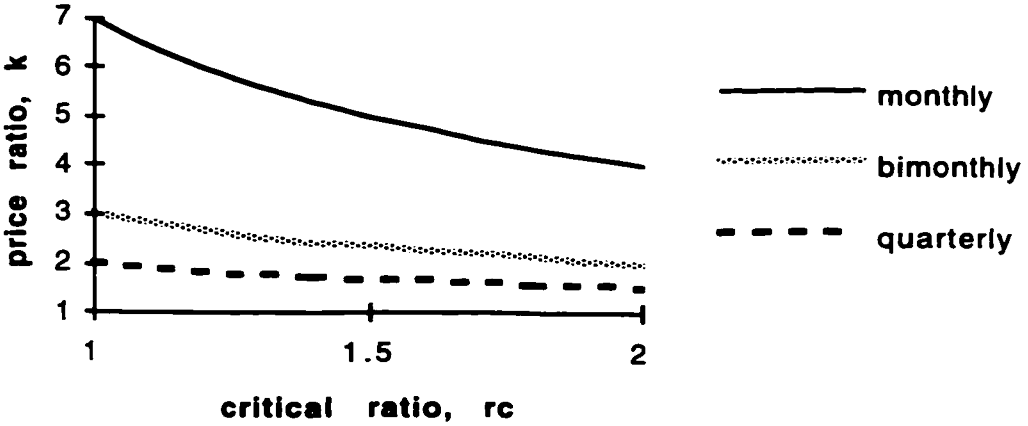


Figure 7.4. Values of the price ratio as a function of the critical ratio which must be exceeded in order for water wastage to financially benefit the customer, based on monthly, bimonthly and quarterly billing.

7.3 Conclusions

The above analysis indicates that the ratio of summer use price to base price, k, must be kept within bounds to avoid inducing significant number of customers to deliberately increase winter water use. The value of the price ratio which must not be exceeded is influenced by the value of the critical ratio, r_c. A somewhat higher price ratio is possible for lower values of r_c. The influence of billing scheme (monthly, bimonthly, quarterly) is harder to assess, since it depends in part on the seasonal distribution of water use by the particular customer. Seasonal distribution data for a sampling of actual customers would be necessary to assess the impact of this analysis on a particular utility.

This analysis indicates conditions under which wastage could lead to customer savings, but does not indicate the amount of the savings achievable. The whole notion of saving through deliberate wastage depends on the precision with which a customer can predict his future water usage with respect to the amount which is likely to be saved. If the expected savings are small, and the uncertainty of savings is large, there will be much less incentive to waste. Because of the customer's uncertainty in being able to anticipate savings, the price ratio, k, could probably be set higher than the theoretical levels suggested by this analysis.

8

Conclusions

This chapter starts with a brief recapitulation of the research problems undertaken in this study. This is followed by conclusions in Sections 8.2 to 8.5. Directions for future research are given in Section 8.6. In the final section, the contributions of this thesis are listed.

8.1 The Research Problems

The main objective of this study was to assess the relationship between urban water demand management and sustainable development. Demand management involves socially beneficial reduction of water use and of water loss from distribution systems. The conventional view is that demand management contributes both to development and sustainability. It contributes to development because, by definition, it is undertaken for social benefit. Social benefits of demand management include cost savings and adaptation to situations of short-term or long-term supply availability. It contributes to sustainability because it reduces the resources needed to support a city. The use of water by the city is less than it otherwise would be. This helps to protect natural aquatic environment. The use of other resources is also reduced. These other resources include those needed for water treatment, wastewater treatment, and for capital expansion related to water supply and wastewater treatment.

Two concepts of development were used in this study. One concept is that development is a process of social problem-solving in which the goal is to improve standards of living. This can be called development by design. The second concept is that development is a process which occurs in complex systems. Complex systems are those which maintain or increase organization through the dissipation of available energy. This type of development can be called development by self-organization.

The concept of sustainable development fits more with development by design than with development by self-organization, since it is about improving or maintaining living standards now and into the future. However, the recognized difficulty with sustainable development, and the reason why it has become the focus of attention generally, is that there is usually a contradiction between short-term and long-term goals.

From a complex systems perspective, economic systems and ecosystems are hierarchically organized systems, open to material and energy flows. These systems maintain their organization by the conversion of high quality energy to low quality energy. Development by self-organization occurs in both economic systems and in ecosystems. It is characterized by increasing specialization of subsystems, increasing rate of resource capture, increasing efficiency, and by an increase in structure. In the complex systems view, development by self-organization in economic systems and ecosystems is not sustainable. As development proceeds, adaptability is traded away for efficiency until a point is reached when adaptability is too low to cope with external perturbations. The system then goes through a crisis from which it emerges with less specialization of subsystems, less ability to capture resources, less efficiency, less structure and more adaptability. The system can then proceed once more to develop. However, the system will be different in greater or lesser degree from what it was before. The development-and-crisis cycle repeats itself in general, but not in detail. In the context of development-and-crisis cycles, development by design cannot be sustainable. From a complex systems perspective then, an assessment of sustainability must include consideration of the ability to regenerate after crisis.

Urban water demand management is one particular strategy of development by design. In order to assess its relationship to sustainable development, it is necessary to know what is to be sustained. Statements setting out visions of sustainability were used as descriptions of what should be sustained. These statements pertain to the Regional Municipality of Waterloo, Ontario, and to the Grand River watershed, which contains the Regional Municipality.[1]

Other issues with regard to urban water demand management in the Regional Municipality of Waterloo became apparent in the course of this study. These provided additional objectives and results: (1) analysis of the integration of demand management into water supply and wastewater treatment planning; (2) simultaneous forecasting of water demand and price with special attention to price smoothing; and (3) a problem inherent in summer use pricing, specifically the possibility that a customer might deliberately waste water to gain financial advantage.

8.2 Urban Water Demand Management and Sustainability

Using community vision statements about what to sustain, the relationship between urban water demand management and sustainable development was analyzed using a complex systems methodology in Chapter 4. The vision statements were taken as statements of design criteria for development by design. The methodology was derived by combining the methodology proposed by Kay and Regier (2000) for assessing sustainability with aspects of complex systems behaviour derived from Conrad's (1983) adaptability theory.

The conclusions about demand management and sustainability from the complex systems approach are, in some ways not very different from the conventional view, but in other ways are quite different:

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[1] These visions of sustainability are reproduced in Appendix B.

(1) current status relative to design criteria

- Demand management helps to ensure that cities are adequately supplied with water. This helps to maintain the well-being of individuals and households.
- Demand management reduces water-taking from the environment. This helps to achieve the vision of local participants with respect to what is desired in the local natural environment, i.e. surface water suitable for Grand River fishery, outdoor recreation and a healthy natural environment.

(2) adaptability (as ability to remain within design criteria)

- Demand management is indirectly (due to promotion of local and global economic development) detrimental to global ecological and resource conditions.
- Water demand management may select for certain types of business activities. This may reduce a city's economic adaptability, if the range of possibilities for future city development is reduced.

(3) capacity to continue to develop

- Demand management results in greater efficiency of resource use. This promotes economic growth and development.

(4) capacity to regenerate after crisis

- Local carrying capacity is not particularly important in the present global economy because so many inputs to cities come from far away. However, local carrying capacity would become more important after a crisis. By disturbing local natural habitats less, water demand management helps to preserve some local ecological and other local natural resource conditions helpful to recovery after crisis.

- Socio-economic crisis involves a rather sudden decrease in societal complexity. Changes which reduce complexity before a crisis might seem like worthwhile long-term goals, but are likely to be competitively disadvantageous in the short-term. Most demand management strategies do not seem to contribute directly to the complexification of socio-economic systems.

It can be seen that this analysis of the relationship of urban water demand management to sustainability does not represent the win-win situation of the conventional view (see Section 8.1).

It is generally accepted that planning for sustainability should involve explicit consideration of environmental issues. Often, an ecosystem approach is advocated. However, it is usual to consider only the natural environmental, most often the local natural environment, to be 'the ecosystem'. The approach taken in this thesis involves consideration of economic systems as parts of ecosystems. In this approach, 'the environment' consists of the natural environment, and also the socio-economic environment.

Urban water planning involves long term decision-making. Current planning periods in the Regional Municipality of Waterloo extend to 2041 in the case of water supply, and 2021 in the case of wastewater treatment. In planning for these extended periods, the possibility of a crisis, or set-back, in economic development should be considered. This is particularly true at present, when there is a growing consensus that world oil production will peak somewhere between 2005 and 2010 (see Subsection 4.3.3). Currently, the spatial scale of planning tends to be limited to the scale at which decisions are taken and implemented by water resource managers. Broad temporal and spatial scales need to be considered in planning for sustainability.

It is beyond the scope of this thesis to consider the severity of problems that might be caused by a reduction in the availability of oil. However, at the least, one should expect that oil will become more expensive. This will have economic ramifications locally and globally. The notion of Hall et al. (1986), referred to in Subsection 4.3.3, concerning resource quality, would provided a useful planning tool. Applied to water, this notion says that water quality can be expressed as the quantity of energy needed to convert it to an economic commodity.

Urban water demand management should be considered as an especially important strategy in a pre-crisis setting. One of the features of a crisis in development by self-organization is a decrease in system complexity. Most demand management strategies do not seem to contribute directly to the complexification of socio-economic systems. In a pre-crisis situation, increases in complexity should be avoided if competition between socio-economic systems permits.

8.3 Case Study on Integrating Demand Management in Planning

This section draws from the case study, found in Chapter 5, of demand management planning in the Regional Municipality of Waterloo. The Region recently undertook two planning studies with the aid of two consulting companies, one for water supply and one for wastewater treatment. Demand management measures were considered in the water supply planning study. A systems view would suggest that water demand management, by reducing water use, has an impact not only on water supply expansion scheduling, but also on wastewater treatment plant expansion scheduling. A case study of this situation was undertaken to look at the integration of demand management in Regional planning. A report was submitted to the Regional Engineering Department (Creese, 1995).

It was shown that water demand management was not being integrated as well as it could be with wastewater treatment planning. Even internally within the water supply study, there was more that could have been done to better integrate demand management. The following conclusions were drawn:

- Integration of the studies would have helped to develop a consistent data base.
- Water demand forecasts were not used in forecasting wastewater flows. Therefore, the effects of demand management measures did not appear as corresponding reductions in wastewater flows.
- Both studies recognized that demand management has the potential to delay expansion of water supply capacity and expansion of wastewater treatment capacity. Neither study tried to evaluate the delay for wastewater treatment.
- The water supply planning study did evaluate the effect of demand management measures in delaying expansion of water supply capacity. However, the schedule of implementation of the demand management measures was not timed for maximum benefit.

It was recommended that care should be taken to select a consulting consortium which considers water use efficiency to be within its central area of expertise.

8.4 Forecasting Demand and Price with Price Smoothing

Future demands for water in the Regional Municipality of Waterloo are forecast without accounting for the effect of price on demand. Demand also has a reciprocal effect on price, mediated by the influence of demand on costs. If large cost increases are anticipated, due to the expansion of water supply capacity, the effect of increased demand on cost is also large. A simulation model, described in Chapter 6, was constructed to represent this situation.

Unlike the models used to forecast water demands for the Region up to the present, this simulation model forecasts prices as well as demands. The model is too incomplete a representation of the real situation for it to have real world application in its present form. However, the present model is a useful starting point.

The simulation model requires as input a population forecast for the city of interest, information on current water use categorized as average day water use, summer day water use and maximum day water use, the current price of water, price elasticities of demand for the three categories of water use, a sequence of capacity expansion steps, and the variable costs and fixed costs for each capacity expansion stage. The output consists of one or more scenarios. In a scenario, each water supply expansion step is assigned to a particular year in the forecast period, and the following are projected for each year in the forecast period: average day water use, maximum day water use and water price. Average cost pricing is used in the model, reflecting the Regional pricing practice.

The model does not in its present form reflect the financing of capacity expansion which actually occurs. Such financing would tend to reduce the probability of large year-to-year changes in water price. In practice, some price changes are still large enough that the Regional Finance Department applies direct price smoothing. Price smoothing is incorporated into the simulation model. The price smoothing which is employed in the model is anticipatory. That is, the price in a given year of the simulation is changed in the direction of future costs, not in the direction of past costs. The time horizon of price smoothing can be set as a simulation parameter.

Once started, the model runs until it has created all the expansion scenarios that it can. The model can save selected evaluation criteria, the schedule of expansion steps, and the time series of average day use, maximum day use and price, for each scenario. The simulation model showed, as expected, that anticipatory price smoothing tends to reduce demand and postpone capacity expansions. When the model was run with price elasticities set to zero, it showed the overcapacity problem which can occur when price elasticity of demand is not integrated with water supply planning.

8.5 Design of Summer Use Pricing

The Regional Municipality of Waterloo has considered various price structures for its programs of water demand management. One of these is summer use pricing, or excess use pricing. The problem analyzed, in Chapter 7, with respect to this price structure was the possibility that a customer might deliberately waste water during winter in order to establish a low base use. The motive for doing this would be that high summer water usage could be maintained without paying the higher summer use price. The value of the threshold used in setting base water use, and the value of the price ratio (summer use price to base use price), are two key parameters controllable by the water utility which are critical in determining whether such deliberate wastage is financially beneficial to a customer. The number of billing periods in the year is also important.

If the value of the price ratio, k, is set as follows, it is not possible to benefit financially from deliberate water wastage in winter:

$$k < 1 + \frac{n_b}{n_s r_c}$$

where n_b is the number of billing periods per year, r_c is the threshold ratio already referred to and n_s is the number of billing periods in which the customer would experience the summer use price without deliberate water wastage in winter. The customer's uncertainty in being able to anticipate savings should permit the price ratio to be set at a somewhat higher value than this theoretical level.

8.6 Directions for Future Research

Adaptive management and anticipatory management have been introduced in this thesis in a rather theoretical manner (Section 3.3, Subsection 4.3.5, Section 4.4). What does adaptive management actually mean for water resource management in the Grand River watershed? How much of what is done now can be considered adaptive management, and how much is anticipatory management? What is the appropriate blend of these two paradigms for current and future situations?

The possibility of an oil crisis within the next decade has been raised. Further work should be done on the effects of a future reduction in oil availability for water resources in the Grand River watershed. To what extent do urban water supply and wastewater treatment depend on oil? How do water and wastewater treatment depend on oil? To what extent do settlement patterns, and therefore urban population forecasts, depend on transportation costs?

The simulation model begun with this research, for forecasting water use and price, could be developed further in one or more of several directions. The most important are (1) to include the financing of capacity expansion, (2) to add the wastewater treatment component of the urban water system, and (3) to include selection of demand management programs. In the Regional Municipality of Waterloo, capacity expansions are funded by water and wastewater charges, but also by development charges. These could be incorporated into the model. The model could be extended to include different price structures. It might be useful, and would be relatively simple in terms of the model structure, to increase the capability of the model to deal with more categories of water use, for example disaggregation by industry type. However, the greater the degree of disaggregation, the greater the difficulty in obtaining the data needed to run the model. Also, for longer forecasting periods, exogenous predictions would be required with respect to changes in the distribution of water use categories. For example, input data could be required for changing mixes of different categories of industrial water use. In the Regional Municipality of Waterloo, there is a two-tier administration of water and wastewater utilities. Expanding the model to reflect this would make it more realistic for two-tier municipalities, but these are in the minority.

The analysis of summer use pricing determined the relationship of the various parameters which would not permit a customer to save money be deliberately wasting water in winter. However, the amount of the savings would be critical in determining the incentive to waste. The research could be carried further by determining the relationship between the amount saved and the various parameters in the analysis.

8.7 Contributions of this Thesis

This study contains a new analysis of the relationship of urban water demand management to sustainable development. A complex systems perspective was applied for the first time to this problem. The particular complex systems methodology used was a new combination based on (1) a concept of sustainability as the ecological integrity of a combined ecological and socio-economic system (Kay et al., 1999; Kay and Regier, 2000) and (2) the adaptability theory of Conrad (1983).

In the conventional view, urban water demand management is thought to be a win-win strategy. It contributes to the economic development of cities by pushing back barriers to growth and it also contributes to the preservation of natural aquatic environments. This study agrees with the previous statement, but goes further. Urban water demand management is not exempt from the contradiction between short-term and long-term goals that is inherent in the concept of sustainable development. From a complex systems viewpoint, neither economic nor ecosystem development is sustainable. Development always eventually leads to a crisis, or sudden reduction in the complexity of the system. The capacity for renewal after crisis is therefore important to assess, and was a component of the description of sustainability adopted for this analysis. Any contribution to economic 'development by design' helps to maintain or improve current standards of living while at the same time following an unsustainable path. However, water demand management does help to preserve local conditions that would be required for renewal after crisis.

Three other problems related to urban water demand management were analyzed as part of this study:

(1) It was shown in a case study from the Regional Municipality of Waterloo that demand management issues could have been better integrated into the process of planning water supply and wastewater treatment capacity expansion. There seems to be a need in urban water system planning for a more collaborative approach among the water supply, wastewater treatment, and demand management areas of expertise.

(2) A simulation model was developed which forecasts water demands and prices simultaneously. Many current models, such as IWR-MAIN developed by the US Army Corps of Engineers (see Opitz et al., 1998), still treat price as an exogenous variable. The model included the situation where capital expansions occur within the forecast period. The unique feature of this model is anticipatory price smoothing. However, the model needs more development before it could be realistically used.

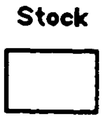
When water system capacity expansions cause price increases, water sales can be depressed sufficiently to change the timetable for capacity expansion. This can be a surprise to municipalities which do not forecast demand and price simultaneously. A model was developed which illustrates this behaviour, using average cost pricing typical of many Ontario municipalities, including the Regional Municipality of Waterloo. Price smoothing, another municipal practice, was incorporated into the model. The model was incomplete from the point of view of not considering financing or including the wastewater system. With these limitations, it was found that anticipatory price smoothing could result in delaying the need for capital expansion.

(3) The water wastage problem inherent in a summer use price structure was analyzed. The relationships among the pricing parameters which could prevent the occurrence of this problem were determined.

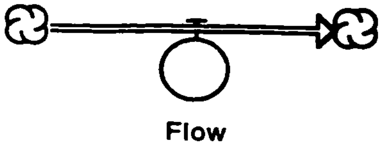
Appendix A: STELLA Modelling Application

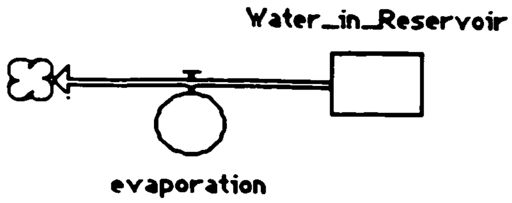
STELLA is an application for system modelling produced by High Performance Systems, Inc. (Richmond, 1985). The name is an acronym for "Structural Thinking, Experiential Learning Laboratory with Animation". STELLA represents an approach to modelling based on what is called either System Dynamics or Systems Thinking (Richmond, 1994).

The basic elements of STELLA models are Stocks, Flows, Converters and Connectors. They are briefly described below.

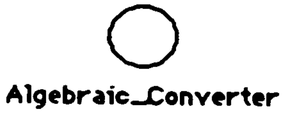


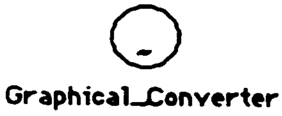
Stocks are STELLA model elements which represent things which accumulate or are lost (i.e. negative accumulation). Mathematically, Stocks represent quantities to be integrated over time. Examples: water in a reservoir, water supply system capacity, sales revenue.





Flows are represented schematically by a pipe which either drains or fills a Stock. Mathematically, a Flow is the time differential of its Stock. Examples: evaporation from a reservoir, development of additional water supply sources, increased sales.





Converters are used to supply input to the model or to get output from the model. They are also used to describe the relationship between elements of the model. Converters can be either of two types: algebraic or graphical. Algebraic converters are used when the relationship between the model elements is easy to describe mathematically, otherwise graphical converters are used.

Connectors appear as straight or curved lines with an arrow at one end. They are used to define how the model elements are to be connected. In the example to the left, the 'Population' Converter consists of a graph of population by year. A Connector must be drawn from the 'Year' Converter to supply input to the 'Population' Converter.

These four STELLA elements are drawn on the computer screen much as in a drawing application. The modeller must then specify the algebraic expressions and graphs for the Converters. STELLA defines the differential equations that describe Stock behaviour, but the modeller must supply the initial values of Stocks.

Many built-in functions are available for use in algebraic expressions. Logical and conditional expressions are possible using the AND, ELSE, IF, NOT, OR and THEN built-in functions. PULSE, RAMP and STEP functions are available for test input. There are random functions NORMAL and RANDOM for stochastic modelling. Smoothing functions SMTH1 and SMTH3 are available, as are a historical TREND function and a trend forecast (FORCST) function. Financial functions include FV (future value), PMT (periodic payment) and PV (present value). There is a choice of three different numerical integration algorithms. Output can be in tabular form or graphical (or both).

Appendix B: Two Visions of Sustainability

Any consideration of sustainability must deal with the question of what to sustain. This appendix contains two sets of statements regarding a vision for the future in the Grand River watershed. One set is from the Regional Official Policies Plan (Municipality of Waterloo, 1998), and the other is from the document entitled "State of the Grand River Watershed: Focus on Watershed Issues 1996-1997" (Grand River Conservation Authority, 1998). A consultative process was used to obtain these vision statements. Participants included municipalities, provincial and federal agencies, the Six Nations, businesses, non-government organizations, universities and the public. Each set of statements can be taken as one indication of what to sustain in the Grand River watershed.

Vision for 2016 (Regional Municipality of Waterloo, 1998)

Planned Growth

The region's population has grown at a steady rate, primarily as a result of people here from the Greater Toronto Area and from other countries. The number of households has grown at a faster rate than the population due to a decline in family size resulting from fewer children per family, more single parent families and more seniors living on their own.

The majority of new development in the region has been concentrated in the urban areas of the Cities and Townships to make efficient use of road, transit, water supply and wastewater treatment infrastructure. New infrastructure has been built to accommodate growth in these areas in accordance with the Regional and Area Municipalities staging plans.

This new development has been accommodated through the re-use of land and buildings in the community cores, and the development of new communities. The new communities combine business and service/commercial uses with residential development that offers a range of housing including townhouses, semi-detached units, low rise apartment buildings and single family houses on smaller lots.

Development has also occurred in rural settlements through in-filling within existing boundaries and through expansion of some settlements facilitated by the construction of communal wastewater treatment systems. This has allowed these settlements to have sufficient population to continue to support some community facilities and services.

Economic Vitality

The region's labour, academic and technological strengths continue to support economic stability. Many traditional businesses have expanded, and new ones have been attracted to the region by a progressive economic strategy. The economic strategy has also focused on training and career skills which enable residents to participate in the changing economy.

Businesses use water conservation and waste reduction strategies, and their operations are supportive of the natural and cultural environment.

Farming the land remains a primary economic activity. Agricultural land and the right to farm have been preserved, while secondary on-farm businesses which do not compromise the viability of the farm are sometimes used to supplement farm income.

Environmental Integrity

Planned growth within defined settlement designations has served to protect prime farm land, significant woodlands, water recharge areas, environmentally sensitive areas and key aggregrate deposits, all of which are important to the economy of the region and to the quality of life of its residents. Areas that are not compatible with development have been defined through watershed plans prepared before new communities are developed.

A network of natural areas has been identified, protected, and in some areas enhanced. This has been achieved through the formation of partnerships including Federal and Provincial Ministries, the Region, the Area Municipalities, the Grand River Conservation Authority, other government agencies, the private sector, and the community.

Water resource protection, management and conservation continue to be primary objectives in the region. Regional residents have been able to reduce their water demands through the installation of water conserving fixtures in homes and the implementation of water saving plans in businesses. The implementation of a Regional Strategy for water resource protection has resulted in improvements to water quality and a reduced likelihood of contaminating groundwater and surface water.

Safe and Healthy Communities

New residential buildings in both the revitalized community cores and new communities are attractive to many regional residents since these new buildings accommodate smaller households, are affordable and well designed. There is a greater sense of community in residential areas with more focus being given to safety, human service needs and transportation opportunities during the planning process.

The balance of jobs and housing provided in compact and mixed land use nodes throughout the community has reduced the need to make some trips and has provided opportunities for a more effective transit service. There is greater comfort and safety for pedestrians and cyclists. Highway and arterial roadway connections continue to be built in concert with the needs of regional residents.

The region is a caring community that offers opportunity and support to all its members including children, the aged, people with disabilities, immigrants and refugees.

Partnerships and Public Participation

Partnerships among government, the private sector and the community have been used to achieve positive change in the region. Recommendations of advisory groups, composed of government, private sector and community representatives have provided meaningful public input into government policies. This means government decision-making is more responsive and widely supported. When making decisions, there is strong recognition of the inter-relationships among the economic, social, cultural and natural environments.

Vision for the Future (Grand River Conservation Authority, 1998)

Population

- The quality of life and sense of place will be maintained.
- Growth will be managed so that it benefits future generations by integrating economic growth, social development and environmental protection.

Business Development

- The watershed will remain a preferred area in which to invest and entice prospective employees.
- A vital rural economy will support and sustain rural communities.
- Tourism, based on heritage and recreational resources, will provide significant economic benefits for rural and urban communities.
- Business development that benefits communities will be encouraged in all sectors.
- Business development will reflect the values we uphold in the watershed.

Water Supply

- Surface and groundwater will be used wisely to ensure that there is sufficient water to meet future needs (domestic, industrial, agricultural, recreational, and natural environments).
- Watershed residents will value water and protect the quality of water.

Water Capacity for Wastewater Discharge

- The river system will have adequate capacity to receive treated wastewater, while also meeting water quality and water supply goals.

Water Quality

- There will a good quality water supply for both urban and rural residents at reasonable cost.
- We will be able to boat and swim in the river throughout the entire system without health concerns.
- We will be able to safely eat the fish.
- Water quality will support a healthy natural aquatic and terrestrial resource.

Flooding

- Flood damages will be reduced.
- Flood prone communities will be prepared for flood emergencies.

Fisheries Resources

- The entire Grand River system will support a healthy, world-class fishery.
- Aquatic resource health and diversity will be indicators of overall watershed health.

- Fisheries management will be based on the aquatic ecosystem approach to managing fisheries.

Natural Areas and Biodiversity

- Habitats will support viable self-sustaining populations of naturally-occurring species. We will not lose any more native species.
- Landowners will value natural areas and understand the management needs of resources on their land.

Outdoor Recreation

- Outdoor recreational opportunities, essential to our health and well-being, will be managed jointly on a watershed basis.
- The entire Grand River watershed system will be recognized as a world-class fishery.
- An extensive network of interconnected trails will be used for hiking, cycling, horseback riding and nature appreciation.
- Watershed visitors will be attracted by the diversity and quality of experiences.

Human Heritage

- We will value the watershed's cultural and human heritage resources, and conserve and interpret them on a watershed basis.
- Human and natural heritage resources will be inextricably linked, such that the natural and human components combine to give a sense of place and community.

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