A System Dynamics Approach to Sustainable Urban Development

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Abstract

The global water crisis – the growing scarcity of fresh and clean water – is receiving increasing attention from both the public and the research community. However, although problems occur both globally and in New Zealand, solutions will be regional in character and specific to urban areas. Availability, distribution, quality, and management of water are problems apparent to many New Zealanders. Finding solutions, however, is made difficult by the complex and dynamic interrelationships of social, economic, environmental, regulatory, managerial, and life-style factors. This paper introduces research in the area of sustainable urban development, with a focus on urban water systems, using system dynamics methodology. System dynamics attempts to model the structure of a system, including its feedback loops and dynamic relationships over time, in order to capture the behaviour it produces. System dynamic models are thus able to effectively deal with the complexities inherent in urban systems. This paper outlines current research in the area, as well as the underlying methodology used.

Keywords: System dynamics, systems thinking, simulation, modelling, sustainable urban development, water infrastructure, water assessment, policy evaluation

1. Introduction

The two most important fundamental needs of towns and cities are a sufficient supply of adequate drinking water and the removal of polluted water. History has shown that if these needs cannot be met, cities rapidly become uninhabitable (Girardet, 2004).

The world water crisis receives growing attention, and the increasing scarcity of clean water has been described as one of the most important issues facing civilization in the 21st century (Simonovic, 2003). However, although the problems are global, the solutions can only be found at regional levels, because water is a regional resource (Simonovic, 2002).

Despite the common perception of abundant water resources and the unlimited ability to treat and dispose of polluted waters, New Zealand is not immune to this crisis. Water shortages, distribution problems due to an aging infrastructure, deteriorating water quality, and inflexible water management are increasingly common. 85% of New Zealanders live in towns and cities, making it one of the most urbanised countries in the world. As a result, solutions to New Zealand's water crisis need to be found in the urban areas.

New Zealand's current water systems were designed and built in the 19th century and have not been improved much since. Especially in Auckland, New Zealand's largest and most rapidly urbanising city, tension is increasing due to fast-paced urban growth and the costs associated with replacing the old water infrastructure and extending it to new areas of urban sprawl (Eason, 2004).

Currently observable trends that aggravate policy-making in New Zealand are the increasing demand for clean water on the one hand and, the limited, polluted water supplies on the other. Institutional and regulatory barriers not-withstanding, the complexities and dynamics present in the system hinder fast and effective policy-making. On the supply side, contamination of surface- and groundwater with uncontrolled or poorly managed stormwater drainage and wastewater disposal decreases the availability of adequate freshwater. The noticeable and increasing deterioration of local water bodies, e.g. streams and rivers, due to persistent pollution (e.g. sediments and toxic substances from stormwater run-off, or illegally discharged industrial trade waste) add to the problem. Note, that water pollution has multiple impacts on the problem; not only does it deteriorate water quality, but it also uses up water resources required for dilution. Water loss of up to 20% through leaking pipes has been reported (Parliamentary Commissioner for the Environment, 2000), and seasonal uncertainties further increase the vulnerability of the water supply. Together these factors may result in an increase in water restrictions, similar to those already in place in some New Zealand areas during the summer. Some even fear potential risk of infrastructure failure (Parliamentary Commissioner for the Environment, 2000). In New Zealand, supply policies have so far focused on delivering more water without incorporating the water's true costs and a market resistance by domestic customers to being charged on the basis of amounts used and disposed of (Parliamentary Commissioner for the Environment, 2000).

The demand for water is growing due to, not only urban growth, but also industrial and agricultural development. Growth in the greater Auckland region is about three times higher than the national average and is expected to increase by 36% until 2021 (Statistics New Zealand, 2002). This growth will result in an increase in freshwater demand. This is largely attributed to an increase in the number of single-person households (Parliamentary Commissioner for the Environment, 2000). Demand will also increase for agricultural and industrial production. As many local and easily sourced water supplies are currently already fully utilised, new sources will often be more expensive, of lower quality, and from more distant catchments (Parliamentary Commissioner for the Environment, 2000).

This research focuses on the assessment of New Zealand's urban water resources and policy choices based on a system dynamics simulation model. Contrary to commonly used assessment models, system dynamics is able to simulate and quantify the dynamic behaviour of complex systems. Although current urban water systems are largely linear, the creation of cyclical elements - similar to the natural water cycle - and the creation of cross-media effects are essential in fostering sustainability.

This paper is organised as follows: Section 2 provides more details on the problem and methodology, and outlines current research on water resources assessment models and relevant system dynamics models. After the introduction of the proposed research project in Section 3, a brief overview is given on feedback received during the conference and how this has influenced the project scope.

2. Literature Review

2.1 Sustainable Development of Urban Systems

The idea of sustainable urban development has emerged because pollution of air, waterways and coasts, and damage to natural ecosystems is escalating, especially in fast-growing urban areas. A considerable amount of confusion exists as to what sustainable development means and implies (Satterthwaite, 1997). A brief definition of the underlying focus is thus indicated. In general, sustainable development is seen as the process of balancing economic and social development with environmental protection. Cities require vast amounts of resources, and so are heavily dependent upon an ever expanding bio-region for their supply. Doughty (2004) argues that cities can never satisfy the four criteria of ’complete’ sustainability as outlined in the “Brundtland” Report (World Commission on Environment and Development, 1987). Here, we adopt a less restrictive definition of sustainability that requires an urban area to be resource efficient and to rely only on products of sustainable production. This could be realised by measures such as energy-efficient buildings, promotion of public transport and walking/cycling, and waste recycling/re-use. This describes the transition from a linear city metabolism to a circular city metabolism.

Urban water systems are defined as ”the natural, modified and built water systems that exist in towns and cities“ (Parliamentary Commissioner for the Environment, 2000). The natural systems include the network of streams, rivers, wetlands, estuaries, and coastal and marine areas. The built system comprises the network of water supply reservoirs, water supply plants, pipes, concrete channels, drains, wastewater treatment plants and outfalls. These two main system parts interact with each other and are also part of a much larger urban ecosystem. This is known as the urban water cycle (Figure 1). Urban water cycles are in turn part of the larger regional and global water cycles.

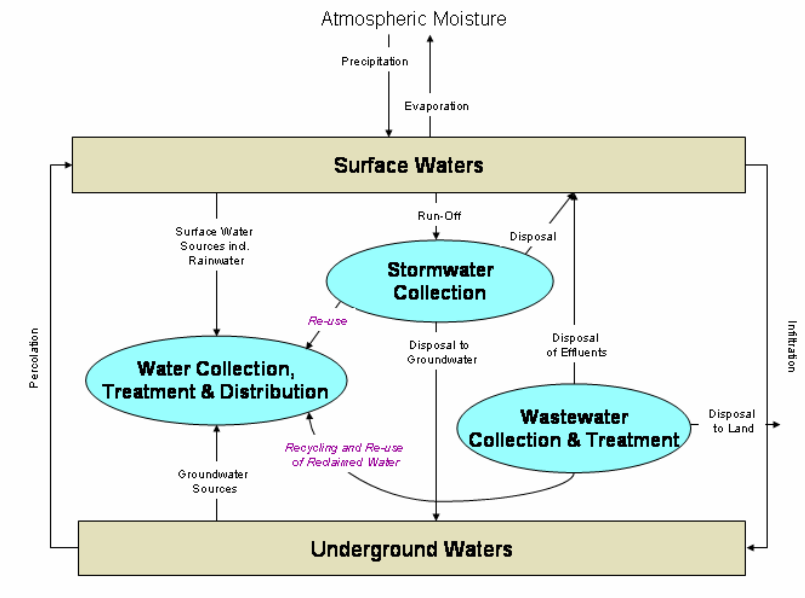

Figure 1: Basic interactions in the urban water cycle (Adapted from Parliamentary Commissioner for the Environment, 2000).

There are different measures that help adopt a circular metabolism in an urban water system. Examples are the minimisation of impervious surfaces, the creation of wetlands, and demand control (Schreier and Brown, 2004).

2.2 System Dynamics Modelling

Systems Thinking and Modelling (STM) is a methodological framework for understanding change and complexity. Systems Thinking has been defined as ”the ability to see things as a whole“ by finding interconnections and being able to explain complexity (Maani and Cavana, 2000). STM is based on the System Dynamics approach developed by Jay Forrester at MIT during the 1950’s by applying feedback control theory to simulation models of organisations (Forrester, 2003). In general, System Dynamics attempts to model the basic structure of a system so as to be able to capture the behaviour that the system produces (Sterman, 2000). It is thus possible to give clear, quantitative cause-and-effect relationships. These relationships are constructed by identifying feedback loops that exist between objects within the system. These can be positive, negative, or stock-and-flow relationships. In feedback loops, a change in one variable affects other variables in the system over time (often including delays), which in turn affect the original variable. Identifying all these relationships correctly and explicitly is the means to understanding complex systems. The research process follows Maani and Cavana (2000), and consists of the following main steps: problem structuring, causal loop modelling, dynamic modelling, and communication of results.

2.3 Water Resources Assessment Models

One of the first steps in addressing the global water crisis is the accurate assessment of available water resources. This forms the basis for future resource predictions and thus, the development of policies to counteract adverse scenarios.

Current water assessment models quantitatively estimate renewable water resources using observed river run-off data (Simonovic, 2004). Leading work on water resources assessment includes, among many others, Gleick (2000), Oki *et al.* (2001), and Alcamo *et al.* (2003). Simonovic (2004) gives two reasons for the inadequacy of these models: the dynamic interrelationships between different factors impacting on water resources, e.g. water use and population growth or economic development, are not explicitly addressed; and the temporal and spatial dynamics are lost in integration. As a result, there is a wide error margin in model predictions.

2.4 System Dynamic Models for Water Resource Management

Several researchers (Ahmad and Simonovic, 2000; Fletcher, 1998; Matthias and Frederick, 1994) have noted the suitability of system dynamics for application to water resource management, because of the inextricably interconnected and intertwined cause-and-effect chains that are apparent in water systems. These chains form a complex system, the properties of which are more than the sum of its constituent parts. The assessment of complex systems calls for an interdisciplinary, dynamic approach. Consequently, recent years have seen the development of a small number of dynamic models for the management of water resources. The two global dynamic models that take water into consideration are TARGETS (Rotmans and deVries, 1997) and *WorldWater* (Simonovic, 2002). TARGETS (**T**ool to **A**ssess **R**egional and **G**lobal **E**nvironmental and health **T**argets for **S**ustainability) consists of five interlinked ’horizontal’ modules representing population and health, energy and economics, biophysics, land and soils, and water. For each horizontal module, four ’vertical’ modules describe the state and dynamics of the system, the pressures on it, the resultant impacts, and the range of policy responses. Its main aim is to study the broad issues of global change and sustainable development.

WorldWater is a pure system dynamics model, and is based on and extends the World3 model developed by Forrester (1971). Results showed a strong relationship between world water resources and world future industrial growth, as well as the fact that water pollution will be the single most important water issue in the future on a global level (Simonovic, 2003).

Simonovic (2003) notes that there is a current trend to focus modelling on regional and basin scales, in order to find regional solutions to the global problem. There are three system dynamic models for very large regions: ErhaiSD (Guo *et al*., 2001) models the Lake Erhai Basin in China, WRSD (Xu *et al*., 2002) models the Yellow River Basin also in China, and *CanadaWater* (Simonovic and Rajasekaram, 2004). All model very large and only partially urbanised areas.

ErhaiSD models a 2,565 km² large region consisting of different land forms (mountains, hills, plains, rivers and lakes). The land is used for farmland (14.5%), forest (44.7%), grassland (20.3%), human habitat (2.7%), transportation (0.5%), and water bodies (9.5%). The purpose of the study was to evaluate four different policy options that were provided by local authorities: (1) no change – base scenario, (2) balance of environmental and economic objectives, (3) increased industrial development, and (4) industrial water pollution control (Guo *et al.*, 2001). The results indicated the quantitative effects of the four choices, but did not yield any novel insights into environmental resource management.

WRSD models a 752,443 km² large region in Northern China. The purpose of the model was to evaluate the performance of the water resources system over a planning period of 30 years, and to assess future water supply and its sustainability in different sub-regions (Xu *et al*., 2002). Ten scenarios of climate change, irrigation improvements, groundwater supply decrease, and water recycling were evaluated. The results showed a need for inter-basin water transfer despite water-reuse options, protection of aquifer recharge areas, and control of deforestation. Social and economic components were not modelled, thus the model can make no statements addressing the effects on the local economy, agriculture, and population.

CanadaWater models the entire territory of Canada plus the United States’ portion of the Great Lakes Basin (~10 million km²) using nine submodels (population, capital, agriculture, food, fresh water, water quality, energy, persistent pollution, non-renewable resources) that were linked together. The purpose was to gain insights into the relationships between Canada’s water quantity and quality, and the main socio-economic variables over a 100 year time span. Twelve scenarios were simulated for different policy options (water availability changes, wastewater treatment, economic growth, energy generation, and food production). Significant findings included the effects of limited gas availability for energy generation, and a general decline in water quality (Simonovic and Rajasekaram, 2004).

3. Proposed Research

This multi-year research is based on the premise that systems thinking and modelling methodology can be applied to the question of urban development in New Zealand, and that it is a valid instrument to assess resources and to identify policies which effectively foster the sustainable development of urban systems, particularly urban water systems. The region modelled is Auckland with its surrounding areas of urban sprawl (Auckland City, Manukau City, Waitakere City, Rodney District, North Shore City, Papakura District), which are representative of other urban regions in New Zealand. 40% of New Zealand's resident population lives in Auckland (Statistics New Zealand, 2002). However, this region is small compared with those from existing system dynamics models for resource management of urban water systems. A model will be developed to address a number of pressing issues faced in the Auckland region: (a) deteriorating infrastructure for water supply and treatment, and associated up-grading costs, (b) increasing water pollution, (c) creation of stormwater resilience and protection, and (d) effectiveness of urban water management policies.

Major research questions that have been identified thusfar are: (1) Which are the major feedback loops operating in urban water systems that influence sustainable development? (2) How much effort in terms of sustainable development is necessary in order to actually improve the quality of the local natural environment? (3)Which policies are effective in fostering sustainable urban development and which are not? (4) How do our simulation results differ with those from other models?

To model all dependencies of the urban water system, several sub-models will be linked together to form an integrated, dynamic water assessment model. The envisaged sub-models are: (1) fresh water, (2) water infrastructure, (3) water quality, (4) marine environment, (5) population, (6) transportation, (7) energy, (8) industry, (9) goods and services, (10) non-renewable resources, (11) pollution, (12) tourism and recreation, (13) climate, and (14) endangered species. Causal links will be identified between different elements in the sub-models themselves, as well as between sub-models, e.g. the impact of increasing impervious surfaces on the groundwater level. This modelling stage will be followed by dynamic modelling and policy evaluation. System dynamics software, e.g. Stella, will be used during this stage. During dynamic modelling a base scenario will be created based on existing patterns of human activities. This will be compared with other scenarios that represent different policy choices. The total planning horizon will be 10-20 years and consisting of time-step analysis in three-month intervals. Time increments of one year, as used in the WRSD and *CanadaWater* models, do not give indications of seasonal variation.

4. Conclusions

This paper introduces research in the area of sustainable urban development with a focus on urban water systems using system dynamics methodology. The research is highly relevant for New Zealand's urban regions. System dynamics models have proven useful for modelling complex problems, and have shown to yield new insights into the management of urban systems and the evaluation of policies. The outcomes envisaged from this research are: (1) a validated model which facilitates the understanding of the interaction between our urban water systems and our society, economy, and environment, (2) the identification of sustainable processes over unsustainable ones, (3) tested policies that foster the sustainable development of urban water systems, and (4) an increased awareness within the wider research community about current research into this problem.

5. Conference Feedback

The conference presentation took place during the Wednesday Urban Dynamics Research Session. The new session format with five minute presentations and following discussion provided valuable feedback, and there appeared to be a lot of interest in the topic. The prevailing argument was that the project scope is too ambitious for a three-year PhD. It was suggested to focus rather on a specific problem instead of simply 'modelling the system' with its many problems. This was discussed with my supervisors and it was agreed to spend more time scoping the project. Currently, the focus is shifting to a policy analysis affecting water quality in urban natural waters, e.g. streams, estuaries, and harbours, due to stormwater run-off.

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