Exploring Scenarios for Urban Water Systems Using a Socio-Technical Model

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ABSTRACT

This paper reports on the ongoing work and research involved in the development of a socio-technical model of urban water systems. Socio-technical, means the model is not so much concerned with the technical or biophysical aspects of urban water systems, but rather with the social and institutional implications of the urban water infrastructure and vice versa. A socio-technical model, in the view purported in this paper, produces scenarios of different urban water servicing solutions gaining or losing influence in meeting water-related societal needs, like potable water, drainage, environmental health and amenity. The urban water system is parameterised with vectors of the relative influence of each servicing solution. The model is a software implementation of the Multi-Pattern Approach, a theory on societal systems, like urban water systems, and how these develop and go through transitions under various internal and external conditions. Acknowledging that social dynamics comes with severe and non reducible uncertainties, the model is set up to be exploratory, meaning that for any initial condition several possible future scenarios are produced. This paper gives a concise overview of the necessary theoretical background, the model architecture and some initial test results using a drainage example which are compared to established theory.

KEYWORDS

Scenario, socio-technical, exploratory modelling, transitions, Multi-Pattern Approach

1 INTRODUCTION

In spite of the established tradition of urban water modelling, it appears that for policy making and strategic planning there still is a lack of appropriate tools. Decision making often relies on stakeholders weighing options and assessing consequences based on their knowledge and expertise. There is nothing intrinsically wrong with this approach, but there is potentially great benefit if there
were tools for a more rigorous kind of thought experimentation. This article reports on the development and first tests of a computer model designed to address that apparent need. Even though reliable models to assess technical performance and design urban water infrastructure are available, they are of limited use when it comes to strategic planning – especially on the middle to long term on large spatial scales. This is due to a number of factors of which two prominent ones are:

1. How urban water systems evolve depends heavily on societal dynamics, which is traditionally regarded external to the models used or unsuitable for a quantitative approach and as such overlooked or disregarded.

2. The larger time and spatial scales, and the societal dynamics bring along many additional interdependencies and irreducible uncertainties, making the use of predictive modelling techniques inappropriate.

All these considerations were the starting point for a research project around the development of an integrated model called DAnCE4Water to assess urban water scenarios and one module in specific – the Societal Transitions Module (STM) – addresses the two issues above.

The STM is designed to model the societal dimensions of urban water servicing (de Haan et al. 2011). It is intended to be used by policy makers and strategic planners to enable transitions to Water Sensitive Cities as conceptualised by Wong and Brown (2009). A transition fundamentally changes the infrastructures and social structures through which societal needs are met (see e.g. Rotmans 2005). The STM draws from the state of the art in transition theorising, the Multi-Pattern Approach (de Haan 2010; de Haan and Rotmans 2011), for a rigorous understanding of the transformative change relevant to urban water systems. Transitions modelling is an emerging field of research (Timmermans et al. 2008; Holtz 2011) and past transitions models have already been successfully employed to study historical and ongoing cases (e.g. Haxeltine et al. 2008; Schilperoord et al. 2008).

Given the complexities and uncertainties in complex socio-technical systems such as urban water servicing, policy and strategic action can have several, possibly un-thought of consequences. The STM can be used to perform rigorous thought experiments to explore such consequences. Consequences deliberately in plural here because the uncertainties involved make it necessary to consider several possible future developments from a single initial state. This kind of approach is typical for exploratory modelling as proposed by Bankes (2009) and Lempert et al. (2003), where quantitative methods like computer models are used to gain qualitative insights like possible future developments.

This paper presents the STM’s development and its application for simulation of transitioning of urban drainage systems from traditional (gutter/pipe systems) to more sustainable systems that include Water Sensitive Urban Design technologies.

2 THEORETICAL FRAMEWORK AND MODEL ARCHITECTURE

As mentioned, the model is a socio-technical model and, as such, not so much concerned with the technical functioning or performance of the urban water system. What is of concern is the societal functioning and performance of the urban water system. People in cities have diverse, water-related societal needs, from basic needs for drinking water and sanitation, to higher level needs like environmental protection and amenity. So, from the socio-technical or societal viewpoint, urban water systems are systems that have evolved to meet those needs. Needs are met, not only through infrastructures, but also through institutions – like knowledge, best practice guidelines and regulations – coupled to those infrastructures. For example, a poorly regulated piped drainage network will be less able to meet the need for flood protection than a well regulated one.
The model conceptualises urban water systems as composite systems, where several subsystems – called constellations – meet several societal needs in different ways. For example, when it comes to drainage, one can think of a constellation meeting drainage needs with pipes and channels and accompanying regulations and hydrological knowledge, and another constellation meeting drainage needs with green infrastructure and the emerging knowledge and regulation involved. Clearly, within each constellation there several water servicing solutions can be available to meet societal needs. In the model these water servicing solutions are combinations of institutions and infrastructures. A specific combination of infrastructure and accompanying institutions is called a facet. For the initial testing of the model the case of stormwater drainage in a small catchment in Melbourne, Australia, was considered. The set of facets identified for this case study is listed in Table 1.

By identifying a constellation with a set of facets the model ‘quantifies’ how well a constellation meets societal needs. A facet takes values in the unit interval, where the value one means meeting the associated need completely, zero meeting it not at all and values in between representing degrees of meeting associated needs.

It is intuitively clear that a constellation with more ways to meet societal needs, or more ability to meet needs in a specific way (e.g. better regulation, more infrastructure) will have more influence in the urban water system. In other words, constellations have more or less power relative to each other. Facets couple infrastructure to institutions and in that way connect the presence of infrastructure with its societal implications: power and meeting of societal needs. This leads to the following interpretation of the power of a constellation: the likelihood a societal need is met through the water servicing solutions of the facets in the constellation.

The above conceptualisation is a direct implementation of the Multi-Pattern Approach (de Haan 2010; de Haan and Rotmans 2011). This theoretical approach views structural change as sequences of a limited number of recurring patterns. The conditions under which these patterns occur depend on how well a constellation meets the societal needs it is supposed to meet (which is called stress), external influences (tension) and how the constellations compete amongst each other (pressure).

The patterns that are formed under influence of these conditions describe how constellations gain and lose power as they evolve to meet societal needs. One pattern describes how a constellation adapts, aptly named adaptation, and two patterns how an alternative constellation emerges. Adaptation describes how incumbent regimes implement new solutions to meet societal needs. The two patterns describing alternatives emerging are reconstellation and empowerment. Reconstellation on the one hand, describes alternatives emerging through powers outside the system, for example government action. Empowerment on the other hand, describes alternatives gaining power within the system, for example through large-scale user adoption.

Within the model, the state of the urban water system at any time is represented by what facets each constellation has and their values. To run a simulation, boundary and initial conditions need to be provided. The initial condition obviously is the state of the urban water system at that time and the boundary conditions are given by scenarios for the societal needs and the external influences.

3 SOFTWARE IMPLEMENTATION AND INITIAL TESTING

3.1 System Representation: Constellations and Facets

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As part of the integrated DAnCE4Water model, this interpretation of power is broadened to the likelihood that new infrastructure to meet the same societal needs will be of the kind represented by the current facets.
The model is explained by presenting its application for simulation of transitions in urban drainage, although it is far more general and could be used for other water systems. Constellations are objects that carry a vector, $\mathbf{c}$, of which the components correspond to facets. The facet basis against which these vectors are measured is user defined and, for the test case here, consists of 5 centralised and 6 decentralised infrastructures, each coupled to 3 types of institutions: cognitive-cultural, normative and regulative, yielding a basis of 33 facets, listed in Table 1.

Table 1. Facets for Drainage Constellations. Each institution combines with each infrastructure, yielding 33 combinations.

<table>
<thead>
<tr>
<th>Institutions</th>
<th>Lineage</th>
<th>Pillar</th>
<th>Infrastructures</th>
<th>Lineage</th>
<th>Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive-cultural</td>
<td>1</td>
<td>0</td>
<td>Centralised Conveyance</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Centralised Primary Treatment</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Centralised Secondary Treatment</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Centralised Tertiary Treatment</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Centralised Harvesting for Potable</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Normative</td>
<td>1</td>
<td>1</td>
<td>Decentralised Conveyance</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Regulative</td>
<td>1</td>
<td>2</td>
<td>Decentralised Attenuation</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decentralised Multifunctional</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decentralised Primary Treatment</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decentralised Secondary Treatment</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decentralised Tertiary Treatment</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

As mentioned earlier, facets represent the way societal needs are met. Moreover, one facet can meet several needs – think for example of water sensitive urban design that meets needs for ecological health and amenity – and possibly to a different extent. This means a matrix can be defined coupling facets with needs. This matrix, $N$, is called the nexus and its entries take values in $\{0, .33, .66, 1\}$, where one means a facet meeting a need (how much is of course dependent on the value of the facet) and less than one implying a facet meeting a need but to a lesser extent, with zero representing the facet not meeting that need, regardless of the value of the facet. The needs themselves are represented by a time-dependent vector, $\mathbf{n}$, taking values on a five point scale $\{0, \frac{1}{2}, 1, 1\frac{1}{2}, 2\}$, with zero to two meaning no need expressed up to high need expression.

Sources of tension are connected to facets in a similar way: one source can potentially impact several facets. Thus, also between sources of tension and facets a nexus can be defined a, in the form of a matrix $\Theta$, taking values on the same four-point scale. The sources of tension are also represented by a time-dependent vector, $\mathbf{t}$, but taking values on a three point scale $\{0, \frac{1}{2}, 1\}$, meaning no, some or extreme tension.

It is now possible to define power in a quantitative manner. The power of a constellation depends on the value of the facets that comprise it, as well as the expression of the needs it meets, as well as the extent to which it meets those needs. In short, the power of a constellation can be calculated by letting
the nexus operate on the facet vector of the constellation and taking the inner product of that result with the societal needs vector at that time.

\[ \Pi = \vec{n} \cdot \vec{N} \cdot \vec{c} \]  \hspace{1cm} (1)

3.2 Model Dynamics: Conditions and Patterns

The model dynamics are driven by the three conditions from theory: Tension, Stress and Pressure. Tension, \( T \), represents how influences from outside the urban water system can be driver for change. In the model that is represented by the sources of tension working on the facets of a constellation:

\[ T = \vec{c} \cdot \Theta \vec{t} \]  \hspace{1cm} (2)

Stress is the relation between a constellation and how well the needs it meets are met, either by itself or other constellations. So, the difference between the total contribution of all constellations’ facets that meet the same needs and those needs, defines a deficit, \( \vec{d} \). This deficit can be, per need, positive (‘over meeting’) or negative (‘under meeting’). Stress, \( S \), can be defined as the inner product of this deficit with itself:

\[ S = \vec{d} \cdot \vec{d} \]  \hspace{1cm} (3)

The last of the three conditions, Pressure, \( P \), is an indication of how much two constellations compete in meeting the same societal needs. Since different facets can meet the same need, there can be competition between constellations around very different water servicing solutions. The measure for this is the inner product of the two facet vectors of the constellations after the needs nexus has operated on them:

\[ P = (N \cdot \vec{c}_1) \cdot (N \cdot \vec{c}_2) \]  \hspace{1cm} (4)

Each of the conditions can trigger one, or more, patterns to transitionally change the system. Tension, representing the impact of outside influences can drive both the reconstellation and adaptation patterns. Pressure, a measure of the impact of competition can lead to empowerment and adaptation alike. Stress, relating to the deficiency of a constellation with respect to the needs it meets can lead to all three patterns. See Figure 1. for an overview of conditions and the patterns they drive.
The change produced by each pattern diminishes the condition that drove it. For example, when pressure drives empowerment it decreases pressure. For each pattern, the model calculates that difference vector that cancels the condition for the constellation on which the pattern acts, that is, the constellation that adapts, is reconstellated or empowered. In the case of empowerment and reconstellation that will be a different constellation than the one that suffers the condition, that is, the constellation under tension, stress or pressure. Therefore for these patterns, two difference vectors are calculated. See again Figure 1. for an overview of the conditions, patterns and the changes to the system.

The invocation of a pattern does not need to lead to the complete transfer of difference vectors and cancellation of the condition that drove it. Rather, the fraction of the maximum change that a pattern can accomplish that actually does eventuate is taken to be proportional to the value of the condition that drives it. For example, if the condition is tension, a factor of $T/T + 1$ times the difference vectors is transferred.

### 3.3 Facet Updating

Obviously, these difference vectors cannot just be added or subtracted from existing constellations. They are vectors of facets corresponding to infrastructures and institutions, simply adding or subtracting them would imply ‘implementing’ infrastructures and institutions regardless of the infrastructures and institutions already present in a constellation. Moreover, implementation of certain infrastructures or institution, presupposes that other infrastructures and institutions are already present. For example, when it comes to institutions (Alderfer 1969; Scott 2008; de Haan, Ferguson et al. 2011;
Ferguson et al. 2011), for any given urban water solution to be implemented, typically first knowledge is acquired (cognitive-cultural institutions), then norms and best practice are identified (normative institutions) before rules and legislation (regulative institutions) are set. Similarly, to implement technology for secondary treatment of stormwater, primary treatment needs to be in place already. Therefore, each facet carries two numbers identifying its place in the lineages of institutions and infrastructures. If a facet is to be added to against the above common sense, the model traces back the lineages and first adds to the facets that precede it. In likewise manner, when subtracting from a facet which would cause it to become negative, the model subtracts the excess from preceding facets.

The model can (although the initial testing described in this article did not make use of this yet) also implement a notion from social psychology which has been adapted to societal systems (Alderfer 1969; de Haan, Ferguson et al. 2011), the notion of a hierarchy of needs. The idea is that some needs are more pressing than others. For example, the need for potable water is more pressing than the need for ecological health, although both are needed. In this way a hierarchy of needs can be identified where groups of needs are more likely to be fulfilled first than others. In the model setting this translates to several ‘orders’ of stress, corresponding to the different levels of needs.

3.4 Producing Multiple Futures

Several conditions can be present, for example there can be stress and tension at the same time. Also, theory does not give strong suggestions which pattern then is more likely to eventuate. The exploratory approach now lies in making use of this uncertainty, rather than choosing a most likely path of development. This implies that at each time step, from one state of the societal system, multiple new states branch out. In the next time step, for each of those new states the same occurs. In this way a tree structure of possible futures emerges, where each path from root to leaf represents an equally plausible, though perhaps counter intuitive, pathway of development. Thus in the main loop, each time step the present conditions (tension, stress and pressure) are calculated. For each condition, if a threshold is exceeded the associated patterns are invoked all leading to a new state of the system which becomes an initial condition in the next iteration.

4 INITIAL TEST RESULTS AND FUTURE WORK

The model is in an early stage of development and it is therefore not possible to discuss any results against an case study yet. Work to date has brought the model up and running, reproducing the theoretically proposed patterns of the Multi-Pattern Approach (de Haan 2010; de Haan and Rotmans 2011). These patterns were originally proposed in a qualitative manner and verification therefore is checking and inspecting more so than measuring and comparing.

For the initial testing two constellations were prepared, one representing a highly centralised subsystem, and another representing a decentralised or green infrastructure subsystem, both around drainage (as per Table 1). To model a powerful presence of centralised infrastructure the centralised facets in that constellation where set to have a value of unity for all their institutional varieties. To model that the decentralised constellation was emerging, its facets had decreasing values for subsequent institutional varieties (1, ½, and .1) representing that although a lot of knowledge is available for decentralised alternatives, norms and regulation are still in development. The power distribution was 70% for the centralised constellation versus 30% for the decentralised one. See Figure 2, for an overview of the initial conditions.

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2 Thresholds were taken to be zero for testing.
To provide boundary conditions against which the modelled urban water system evolves, scenarios for the water-related societal needs, $\eta(t)$, and sources of tension, $\tau(t)$, need to be provided. The needs for this case are Potable Water, Public Health, Non-potable Water, Property Protection, Ecological Health, Amenity and Intergenerational Equity. Societal needs, $\eta$, can take values in \{0, $\frac{1}{2}$, 1, 1½, 2\}, possibly varying over time. This is to model that, although societal needs are always present, they might be more or less expressed under different circumstances. A value of zero implies that the need is not expressed at all, one it is ‘normally’ expressed and two a highly expressed need. The programme reads a time series for each societal need from a comma-separated values file and creates an object that can be queried for the expression of the needs at a specific time. Sources of tension, $\tau$, which in this case is only Lack of Resources, take values in \{0, 1, 2\}, where zero means the source is producing no tension, one, some tension and two, significant tension. Sources of tension are read from a comma-separated values file as well and made accessible through a similar object. The boundary conditions were taken to be constant throughout the simulation and such that the centralised constellation was under a condition of constant tension. Also throughout the simulation, some societal needs were insufficiently met, causing the condition of stress. That the two constellations were meeting some of the same needs caused constant pressure. Thus, during the test runs all conditions for transitional change were present and the different patterns could form.

Space constraints do not allow an overview of all the patterns working on these initial conditions. For purposes of illustration see Figure 3 and Figure 4 for examples of the effects of patterns on the power distribution of a modelled system.

In these cases the patterns work under the conditions of tension or stress resulting in the growth of alternative solutions at the expense of the current most powerful constellation. This also diminishes the tension and stress in the system since the alternative solutions are not affected by the sources of tension and the previously insufficiently met needs.

Figure 2. Initial Conditions.
The model and test runs presented are the initial results of this project’s socio-technical modelling ambitions. Highly stylised initial conditions and scenarios were used that have, as yet, no proper connection to real world data. The simulated patterns, however, seem to behave as theoretically expected and the next stages of the model’s development have commenced. These entail more systematic testing and investigating the capacity of the model to produce scenarios from sequential application of the patterns. This will be tested against a case study of the historical development and partial transition to water sensitive urban design in the catchment of Scotchman’s Creek in Melbourne, Australia.

5 ACKNOWLEDGEMENTS
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6 REFERENCES


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