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Modeling water resource in the Australian Capital Territory: Knowledge elicitation for system dynamics model building

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Abstract

The Australian Capital Territory (ACT) has found its water supply threatened by prolonged drought, bushfires and increasing consumer demand. In future, risks will escalate as a consequence of climate change effects and continued population growth. Strategies which seek to reduce the *per capita* demand for water, and ideally to limit total consumption, appear to be obvious ways of achieving water resource sustainability.

Programs which focus on improving the effectiveness in communicating to consumers how water availability is threatened are considered to be an essential part managing demand and ultimately consumption. Effective communication aims to increase public understanding of the problem whilst better informing local decision making and public acceptance of strategies which might be imposed in future to manage scarce water resources. As this problem is inherently complex, effective risk communication is problematic both for those developing management strategies and those who may have such strategies imposed upon them.

Advances in computer modelling and simulation, supported by rapid progress in Information and Communications Technologies (ICT) provide unprecedented opportunities for demonstrating to the public the complex interrelationships between supply and demand for water. System Dynamics (SD) modelling is a promising approach for enabling learning and communication. While SD is often used to analyse the dynamics of systemic problems and assess policy options, its potential for communicating systemic risks to the public has not been fully exploited.

The ongoing research described in this paper aims to develop a SD-based interactive learning tool to help ACT residents develop a systemic perspective of the water management problem and to demonstrate plausible futures they might face. Expected outcomes of this research are an understanding of options for facilitating dialogue among stakeholders, effectively promoting water-wise attitudes and ultimately influencing consumer behaviour.

This paper describes the methodology used to collect, analyse and merge views elicited from stakeholders (i.e. users and managers) and to form them into a conceptual causal feedback representation of the problem. This representation forms the basis for subsequent stages in which quantitative models and computer simulations will be developed. The methodology has three stages. Firstly, a preliminary conceptual model was developed based on the systems thinking (ST) and SD literatures. Secondly, local and expert knowledge was captured by eliciting the perceptions of water users (n=25) and managers (n=10) in the ACT using semi-structured interviews. Cognitive Mapping techniques were used to depict participants' perceptions. Finally, noting the potential pitfalls of doing so, the various views were represented in a single conceptual model. An electronic workbook was also used to investigate stakeholders' perceptions of the causal relationships between selected strongly coupled variables and for obtaining estimates of selected parameters needed for subsequent quantitative modelling activities.

The ST/SD modelling used in this research is distinguished by the following: as an action research inquiry and that it seeks to demonstrate the *recoverability criterion*. That is, whilst it is neither possible to comprehensively validate the research findings nor precisely replicate the research elsewhere, every step in the research journey is traceable. Hence understanding of problem and the manifestations of its complexity are enhanced as are the insights into how to develop and implement effective risk communication strategies.

Keywords: *Water management, System Dynamics modeling, knowledge elicitation, Australian Capital Territory region*

1. INTRODUCTION

The ACT was built early in the 20th Century to house the Australian Federal Government and its public service. Being the largest urban centre in the Murray-Darling Basin (population of 360,000) and seat of the Commonwealth Government (Cooper, Tanner et al. 2007), the water security of the Australian Capital Territory (ACT) is critically important. From 2003 to 2009 the ACT experienced a serious decline in average runoff (i.e. 25% below the historic average). In 2003, the situation was exacerbated by bushfires unprecedented in recent history. These bushfires burnt the vast majority of the ACT catchments. In 2006 the ACT witnessed the lowest inflows on record (Cooper et al., 2007). In order to meet demand, the region has significantly drawn on the volume of water in storage. In future, the ACT will be faced by growing pressures on the water supply and demand sides, including prolonged droughts, climate change effects and population growth.

Management options may be broadly categorized into: increasing supply or reducing demand. On the supply side, the ACT government continues to investigate a variety of supply options. As an inland territory, options are limited for the ACT to initiate capital and energy intensive projects, such as building a new dam and purchasing cross-borders water. However, the long term sustainability of these solutions is seriously challenged by the evolving climate change, likely ecological damage and economic uncertainty.

On the demand side, the government set targets of 12% reduction in per capita consumption by year 2013 and 25% reductions by year 2023 (Government 2004). A combination of demand management strategies, including price signals and water restrictions are being used. Despite their perceived success is achieving immediate responses, economic and regulatory instruments are not sufficient for fostering resilient and voluntary behavioural changes. Communication strategies are essential part for achieving long term reductions (Dietz and Stern 2002).

With the increasing recognition of the substantial role of public participation in sustainable water management, communication strategies seek to increase public understanding about the problem, its underlying causes, potential effects and mitigation strategies. To enhance awareness, the community needs to know which of a set of equally plausible futures they could face (Hjorth and Bagheri 2006). Improved understanding of cause-and-effect relationships is expected to promote better informed decision making, facilitate dialogue among stakeholders and public involvement (Stave 2002). Nevertheless, the problem of managing demand under conditions of highly variable and uncertain supply is inherently complex. The existence of a range of causal drivers which underpin the uncertainty, serve to exacerbate the challenge of effectively communicating the risks to water management to the public.

System **D**ynamics Modelling (**SD**) stands as a promising approach for designing interactive solutions that communicate complexity and uncertainty. It provides a methodological framework for learning about complexity and change by eliciting, representing and analysing the cause-effect structure underlying systemic problem situations. A simulation model is created to explore a system's behaviour in response to different management policies and plausible futures. Whereas SD is often used to help experts (i.e. engineers and decision-makers) model the dynamics of water behaviour, their potential for public communication has is yet to be fully exploited (Stave 2003).

This research project aims to design a SD based simulation game in order to assist ACT water users in developing a systemic perspective on water management, which may promote more informed decision making and public participation. A demand-centred focus is a key element which distinguishes this research from any other efforts for water modelling in the ACT. Thus, the simulation game is not intended to support design or planning for water supply systems.

This paper focuses on the methodology developed to collect, understand and merge viewpoints coming from different stakeholders (i.e. users and managers) in order to build a conceptual representation of the system. The developed conceptual model acts as a basis for quantitative model building. The model development uses the following steps: (1) Designing a preliminary conceptual model, (2) Eliciting local knowledge, (3) Eliciting expert knowledge, (4) Building a conceptual model and (5) Designing a workbook to aid knowledge elicitation and parametric estimation, essential in the absence of hard data.

The paper is organized as follows: SD modelling is presented in section (2). The relevance of knowledge elicitation in model building is highlighted in section (3). The adopted modelling process is described in section (4). Finally, we address the conclusion and learning lessons.

2. SYSTEM DYNAMICS MODELLING

System Dynamics is a methodological framework for learning about complexity and change by eliciting, mapping and analysing the problem structure (i.e. the cause-effect structure underling the problematic behaviour) (Sterman 2000). Simulating the SD model shows the delayed and systemic impacts of alternative policy levers on the system behaviour in a time-compressed manner (Sterman 1994).

SD provides a set of qualitative and quantitative techniques for communicating the complexities of water management to non-experts, such as causal loop mapping and simulation games. Using an interactive gaming interface, users are positioned to play roles that they could not experience in reality to self-explore the problem and the outcomes of different management policies. Integrated with a series of scenarios players can communicate and foster dialogue about plausible future scenarios, and test and discuss appropriate management and policy responses. While SD is often used to help experts (i.e. engineers and decision-makers) model the dynamics of water supply and assess policy options (Elshorbagy, Jutla et al. 2007), its potential for public communication has not been fully exploited (Stave, 2003). Only few cases can be found in literature (Stave 2003; C.Tidwell, Passell et al. 2004; Williams, Lansey et al. 2009).

3. KNOWLEDGE ELICITATION FOR SD MODEL BUILDING

SD model building is a combination of iteratively progressed phases of problem structuring, quantitative modelling, testing and refinement designed to identify the key factors and interrelationships driving the target (problem) behaviour (Sterman 2000). Much of the relevant information about the problem structure is deeply rooted in the stakeholders' minds and may not be explicit; it the stakeholders may not be explicitly aware of the factors driving their behaviour. Although SD models are mathematical representations, qualitative data about the stakeholders' knowledge (i.e. mental database) have always been regarded as crucial input for effective model building (Forrester 1992). SD makes use of a wide range of knowledge elicitation techniques (e.g. interviews and focus groups) through the different model building phases (Luna-Reyes and Andersen 2003). (Vennix 1990) described the Delphi-based method used for problem structuring. (Ford and Sterman 1998) presented a detailed articulation of knowledge elicitation process used for equations specification and parameters estimation.

4. THE ADOPTED MODELLING PROCESS

This research follows a structured and transparent modelling process augmented by semantically rich ‘‘real world’’ interviews and cognitive mapping (Eden and Ackermann 1998), analysis of causal structures through an integrated approach using qualitative modelling and quantitative SD modelling and simulation (Mclucas 2001; Mclucas 2003; Mclucas 2005). The methodological roots for this process are grounded in soft operations research and SD literatures with particular emphasis on SODA (Strategic Options Development and Analysis), Cognitive Mapping and SD (Coyle 1996; Sterman 2000). Designed as an action research, we strive for a recoverable research process through which the methodological details and potential outcomes are well-declared to audiences (Checkland 1998).

The modelling process started by designing a preliminary model and cascaded through a series of knowledge elicitation tasks in order to reach a conceptual representation of the problem. This work was done over one year period. The overall adopted modelling process and outcomes are depicted in Figure 1, with chronological order from [Step 1] through [Step 13].

4.1. Preliminary Model Design

As a departure point, a preliminary model was created to articulate the problem based on relevant literature [Step 1]. This model was the basis for structuring the questions used for subsequent data collection [Step 2]. Figure 2 represents the preliminary model.

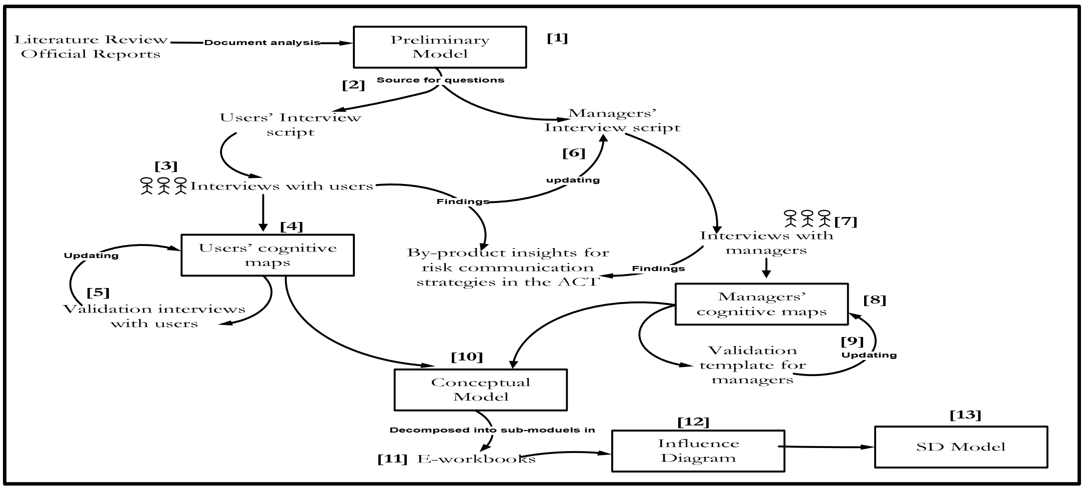

Figure 1: Overview of the modelling process

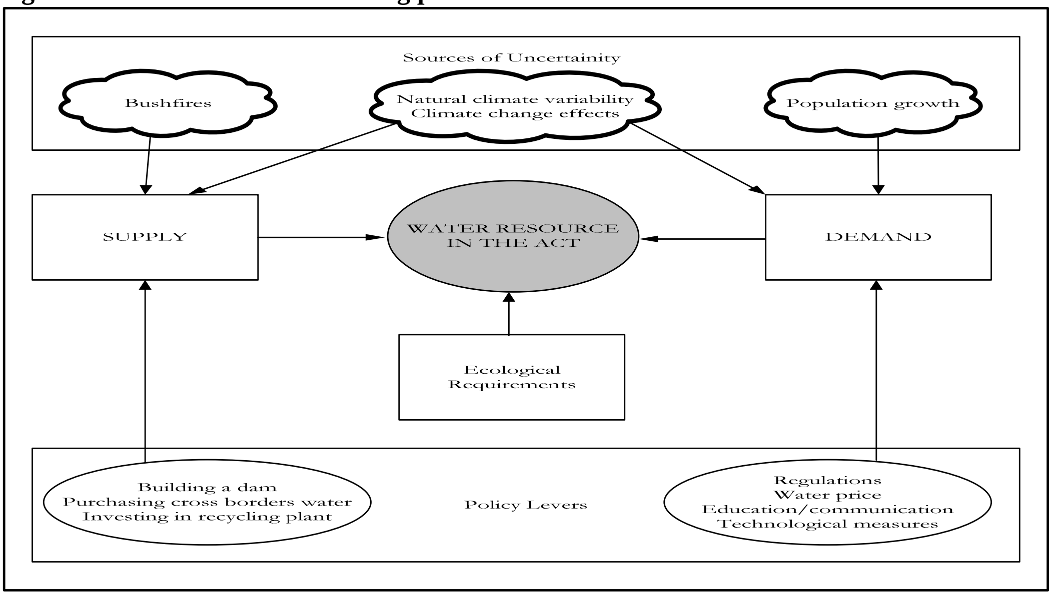

Figure 2: The preliminary model developed at the outset of the research project

4.2. Eliciting Local Knowledge

Local knowledge or public perceptions constitute not only a rich and but a legitimate problem representation (Garvin 2001). If users' perceptions provide the basis for their behaviours then their perceptions are critical for water management. In risk communication literature, effective communication interventions are preceded by a deep investigation of the audiences' existing knowledge and beliefs (Morgan, Fischhoff et al. 2002). Therefore, the purpose of this knowledge elicitation task was to capture users' perceptions about the problem causes, effects and potential mitigation strategies.

A semi-structured interview probed around a set of anchor topics was used to gain an understanding of the extent of participants' knowledge. The interviewing process was conducted as two sessions. The main session (45-60 minutes) was used to data collection [Step 3]. Interviews were transcribed and organized into cognitive maps [Step 4]. Figure 3 illustrates an example of a user's cognitive map. A second session (20-30 minutes) was organized to validate the developed maps, refine language ambiguities and ensure consistent terms. Users were invited to give feedback about their cognitive maps which were updated accordingly [Step 5]. A detailed description of this step can be found in (El Sawah et al, 2008). Findings were used to generate more questions in the managers' interviews script [Step 6].

4.3. Eliciting Expert Knowledge

Expert knowledge has been increasingly recognized as an important input for informing and guiding environmentally related decisions (Fazey, Proust et al. 2006). Through their experience, experts have acquired extensive knowledge about the dynamic complexity of water management and adaptation policies. At this step, we aim to capture this wealth of knowledge using a semi-structured interviewing process (45-75 minutes) [Step 7]. Ten highly experienced managers were recommended by the water management authority in the ACT for participation in the study. Their expertise covered the main business sectors including: supply, demand, and quality management. Six participants were distinguished for their cross functional knowledge, compared to others whose knowledge was focused on a specific area of expertise. Interviews were transcribed and organized into cognitive maps [Step 8].

Because of the managers' tight schedule, a second validation session could not be organized. Alternatively, an electronic validation template was prepared to summarize the key causal assertions extracted from their maps. Managers were asked to accept/reject relationships and justify their choices. Cognitive maps were updated according to the results of the validation template [Step 9].

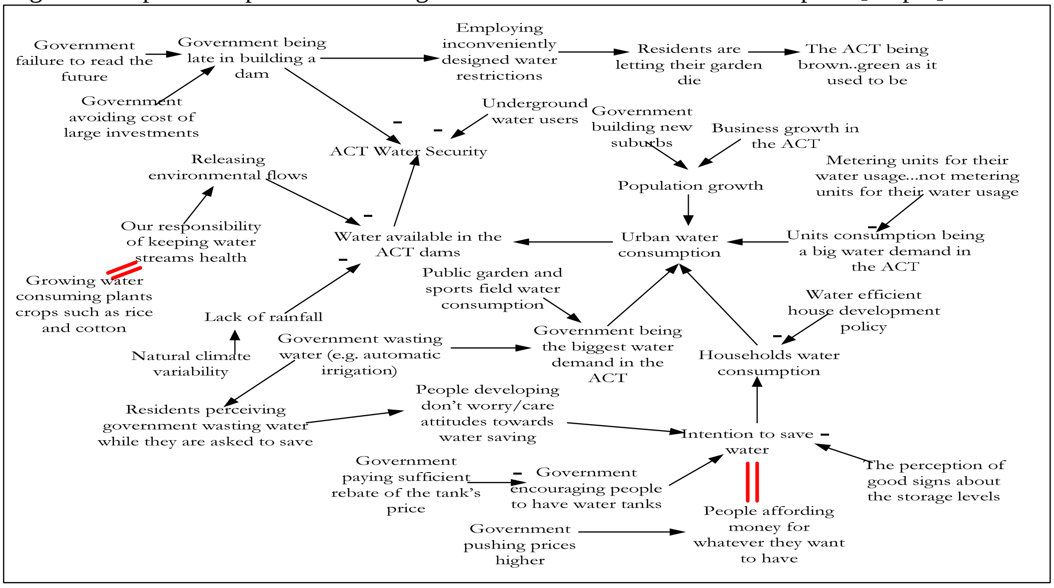

Figure 3: An illustrative example of a user's cognitive map.

4.4. Building a Conceptual Model

The purpose of this step [10] was to create a conceptual model for the problem in order to: (1) model the knowledge and arguments discovered so far, merging the various views so that "synergy" and creativity become possible; and (2) sharpen the authors' understanding about the dynamics of the problem and the appropriate level of details for quantitative model building. In the literature, these representations (known as "cause maps") are often built in group settings at which different groups can contribute directly to map building by capturing views, negotiating and reaching a consensus (Howick, Eden et al. 2008). Whereas this step was planned in our original methodology outline, these focus groups were not run because of time constraints for the water managers. A process of comparison, aggregation and merging was undertaken by the modellers to create a shared representing without suppressing the inherent diversity*. The conceptual model highlights the perceived gaps and overlays in the perceptions of managers and users. For example, while users believed that investment in building a new dam will automatically lead to additional inflows to the reservoirs, managers challenged this assumption considering other rainfall-independent supply sources as the best strategy to cope with climate change effects. Figure 4 shows the developed conceptual model.

4.5. Designing a workbook

This step focused the analysis on those elements in the conceptual model on which participants did not agree [Step 11]. Our purpose was to scope the key variables and causal relationships which were candidates for quantitative modelling. The electronic workbook contained 4 sub-models, centred on four decisions (dependent variables) in the conceptual model: water supply, water demand, water quality and total costs. Participants were invited to accept/reject or add variables to each sub-module. The data is used to build a series of influence diagrams [Step 12] depicting the behaviour of the four variables. These influence diagrams provide the basis for building a SD model [Step 13].

* The term conceptual model rather than cause map is used to distinguish the developed representations from maps built in group settings.

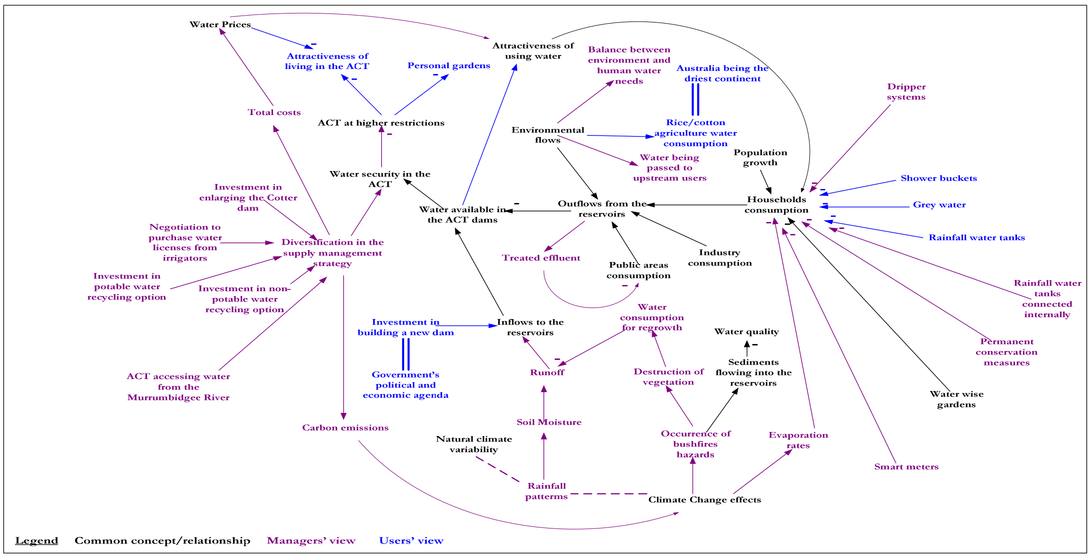

Figure 4: A conceptual framework of the problem as perceived by water users and managers.

5. CONCLUSION AND LEARNING LESSONS

The goal of this ongoing research is to communicate a "big picture" understanding about the evolving risks of water scarcity in the ACT using a SD based game. We follow a transparent modelling process which cascades from rich individual views and cognitive maps to qualitative models to a formal quantitative model. Through this process, stakeholders' knowledge is regarded as a crucial input for effective model building.

This paper reports the knowledge elicitation process used to collect different, understand and merge different views into a conceptual model. First, a preliminary model was developed based on content analysis of relevant literature. A series of semi-structured interviews were conducted to elicit the perceptions of users and managers. Cognitive mapping technique was used to map the elicited data in terms of causal assertions about the problem. Whereas a second interviewing session was organized to validate users' maps, an electronic template was designed to validate managers' maps because of their tight schedule. The collected data was used to create a conceptual model. Finally, an electronic workbook is used to scope the key variables and interrelationships which are candidates for quantitative modelling. In the next stage, data collected from the workbooks will be used to develop a series of influence diagrams, which will be directly mapped into the SD model.

Early indications are that the research methodology is proving to be highly effective from an analytical viewpoint. Critical factors in achieving the research aims are:

1. Having the resources to engage with a sufficiently large set of stakeholders to elicit their mental models and capture them in cognitive mapping format. These activities are time consuming and labour intensive.
2. Engaging sufficiently with stakeholder groups, both managers and consumer to ensure the knowledge capture processes are comprehensive.
3. As far as it is possible, validating the SD models.
4. Designing the simulations in ways that engage players and realistically test their decision making skills.

These factors are being address as the research proceeds. So far, we obtained two pragmatic lessons from our experience through this modelling effort. *Lesson 1: The modelling process must be flexible and adaptable with several research and real world trade-offs.* Although managers' input is considered a critical element to the research process, it was very hard to intensively engage them in the research activities (e.g. focus groups). We altered some of the research activities to balance between the results' validity and maintaining a good relationship with out client, such as using e-workbooks and validation templates. *Lesson 2: The modelling process may have many by-product outcomes.* Knowledge accumulated through the different elicitation cycles illuminated many useful insights for guiding the design of public policies about the attitudes of users towards water conservation policies and the gap between local and experts' perceptions.

Finally, simulations will be comprehensively tested and before being demonstrated and made available for public evaluation in mid-2009. Internet- accessible simulations will be used to gather data about how players adapt to possible future scenarios. Subsequent stages of the research will test the extent to which player learning influences their behaviour as water consumers.

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