Understanding the Complex System Dynamics of Managing Water Security

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Abstract. In many parts of the world, assuring reliable supplies of potable water is a serious challenge. It is not simply a matter of imposing restrictions on supply, increasing water prices, and building new dams. Effective water security strategies can only be developed when the mechanisms of supply and demand and the interactions between are fully understood. A System Dynamics (SD) modeling approach is taken to collect, analyze and merge the views of both consumers and supply managers in order to develop conceptual models which then form the basis for building quantitative models to investigate the complex dynamics. The modeling process has led to a significant increase in the understanding of the management of water security. First, the process has reinforced a number of lessons learned by SD modelers over the years, and second, the process has exposed a significant number of mis-perceptions about water security among supply managers and consumers.

The Australian Capital Territory Region

The ACT was built early in the 20th Century to house the Australian Federal Government and its public service. It is growing rapidly and is currently home to some 360,000 inhabitants, numerous commercial and industrial enterprises and a smaller number of rural and agricultural activities (Cooper et al., 2007). The ACT lies entirely within the Upper Murrumbidgee River Catchment. The Upper Murrumbidgee covers an area of 13,000 square kilometres, of which the ACT occupies 2,400 square kilometres (ACT Government, 2004b). The Murrumbidgee River rises in the south western part of the catchment. The ACT is bordered by, and shares many of its resources with, several smaller towns, villages and rural communities. As an inland territory, the ACT is rainfall dependent region with most (60%) of its water supply is drawn from the Cotter catchment. Over the last seven years, the ACT has experienced a dramatic decline in average runoff from rainfall (25% below the historic average). In 2003, the situation has been exacerbated by bushfires, unprecedented in recent history, which burnt the vast majority of the ACT catchments. In year 2006, the ACT has witnessed the lowest inflows in records (Cooper et al., 2007). In order to meet demand, the region has significantly drawn on the volume of water in storage.

In response to this crisis, a strategy of securing water to the ACT has been initiated. Through this strategy, the focus is placed on supply management: the ACT government has set targets of 12% reduction in per capita consumption by year 2013 and 25% by year 2023 (ACT Government, 2004). To achieve these targets, demand management strategies have been implemented. These include imposing incrementally staged water restrictions and setting up a pricing structure which penalizes those who consume most.

System Dynamics Modelling

System Dynamics (SD) is a methodological framework designed to facilitate learning about dynamic complexity. SD seeks to reveal the underlying causal structure of the problem being investigated. SD problem conceptualization involves eliciting, mapping and analyzing the cause-effect structure giving rise to the observed problematic behaviors. Simulating the SD model shows the delayed and systemic impacts of alternative policies and strategies on system behavior.

Through both qualitative and quantitative techniques, SD enables communicating the complexities of water management to the lay person. Techniques include causal loop diagrams, dynamic modeling and time domain simulations. The creation of an interactive gaming interface, also termed *Management Flight Simulator* or *Micro-world*, offers the opportunity to position players in roles they could not experience otherwise. In this way players can test how their chosen behaviors, or management policies, might produce systems responses well into the future. In the case of this research, simulations can be run to represent up to 30 years into the future.

Whilst the modeling described here has been used to examine the dynamics of water supply and assess policy options (Elshorbagy et al., 2007), system dynamics modeling and simulation games derived from such models are yet to be fully exploited as tools for enhancing communication about public policy (Stave, 2003). Few cases can be found in literature such (Williams et al., 2008), (Stave, 2003) and (Tidwell et al., 2004).

Rarely do members of the public, who can be either the unwitting beneficiaries or victims of public policy decisions, have an opportunity to test for themselves the likely efficacy of alternate management policies. Experience gained through this research suggests that the problems faced jointly by both regulators and communities can be readily misunderstood and, as a consequence, the formulation of policies can be flawed.

Knowledge Elicitation as the Conceptual Basis for Model Building

System dynamics methodology involves iteration through a series of phases: problem structuring, quantitative modelling, testing and refinement in order to acquire a deep understanding of the key factors and interrelationships deriving the problematic behaviour (Sterman, 2000).

Although each computational SD model is necessarily a mathematical representation of a single perspective, the evolution of the model draws on qualitative representations of stakeholders' understandings, that is, as held in stakeholders' minds as mental models. Capturing these mental models and translating them into causal representations which enables the building of a computational model has always been regarded as being critical for both for understanding causality underpinning the problem being analysed and for effective model building (Forrester, 1994).

SD can draw upon a wide range of knowledge elicitation techniques including interviews and focus groups, expert knowledge elicitation, parametric estimation, and problem structuring, with each making its own contribution to learning about the problem (Luna-Reyes and Anderson, 2003; Vennix, 1996; and Sterman, 2000). The methods used, including multi-methodological approaches seek to capture the richness and complexity of the problem involved before reducing it to the essential cause-and-effect feedback structures to be analysed using computational modelling. SD is unique in that it seeks to iterate through the conceptual and computational modelling stages to enhance learning about the effect that feedback dynamics have on the changes over time that are of interest to the observer, analyst or stakeholder in a problem.

The Modelling Process Adopted in this Study

This research follows a structured modeling 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 modeling and quantitative SD modeling 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). Interventions such as this are best classified as action research, where it the aim is to satisfy the *recoverability criterion* (rather than attempting to establish *truth*, which is impossible when dealing with highly complex problems) (Checkland and Holwell, 1998; Checkland and Pouter, 2006). That is, the research always seeks to fully demonstrate, or show ability to recover, the results achieved through all stages.

The modeling 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 modeling process and outcomes are depicted in Figure 1, with chronological order from [Step 1] through [Step 17].

The literature review including reports on previous work led to the identification of key cause-and-effect drivers and the creation of a preliminary model. This model guided the planning for conducting interviews with water consumers or users and with water resource managers. The results from pilot set of interviews with each of these groups informed the re-design of the interviews and the elicitation of cognitive maps. Whilst the cognitive maps were found to contain many shared ideas about cause-and-effect, parts of the problem space were perceived quite differently by the various participants in the study. This was the case particularly for the managers group who had developed more intricate and complete cognitive maps. Investigating this further in the limited time available to managers demanded the development of electronic work books which managers were asked to complete. They were able to do so in a short time. This proved effective in enabling the capture of the specific detail relating to cause and effect relationships and also provided the basis for some parametric estimating. A system dynamics influence diagram was constructed as a result. This formed the basis of the design of the system dynamics model, though the completion of the system dynamics modeling required comprehensive formulation of the vast number of algebraic relationships which the model would eventually contain. In subsequent stages, the model’s structure and the algebraic relationships which link all parts of the structure would have to be verified to assure correct functionality. The model would also have to be verified to assure that it was a sufficiently faithful representation of the mechanisms which drive real-world supply and demand and the interrelationships which create the dynamics that consumers and managers alike so often find to be confounding.

Preliminary Model Design

The preliminary model served to enable qualitative analysis and the subsequent building of the computational system dynamics model. The qualitative model described the broad issues which are deemed necessary to understand the problem, including:

- Uncontrollable drivers: climate change and population growth.
- Management policies: supply and demand management option

This conceptual model, Figure 2, provided the basis for the design of specific questions aimed at subsequent data collection (El Sawah et al., 2009; Vennix, 1996:102) [Step 2].

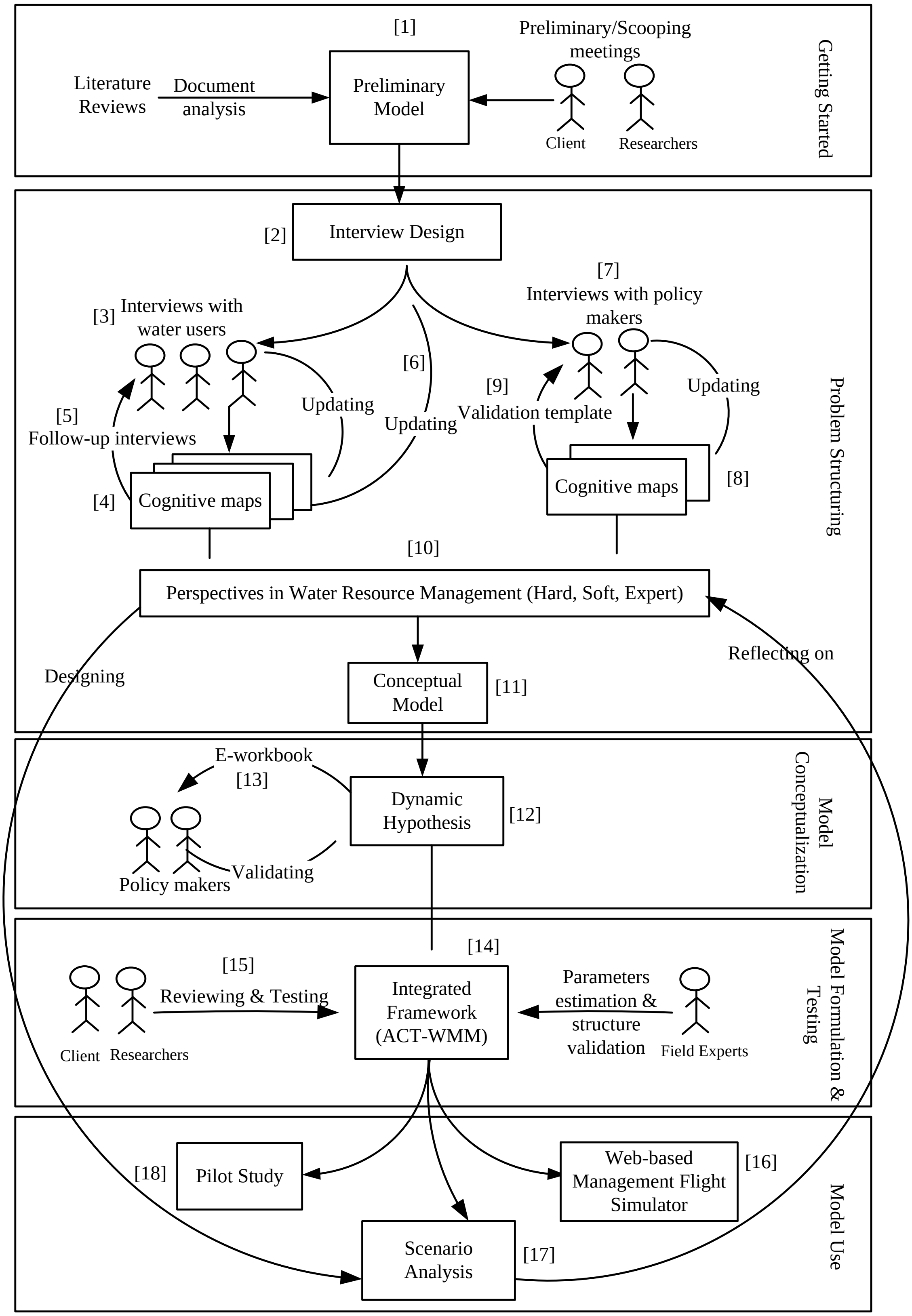

Figure 1: Overview of the modeling process adopted in this research.

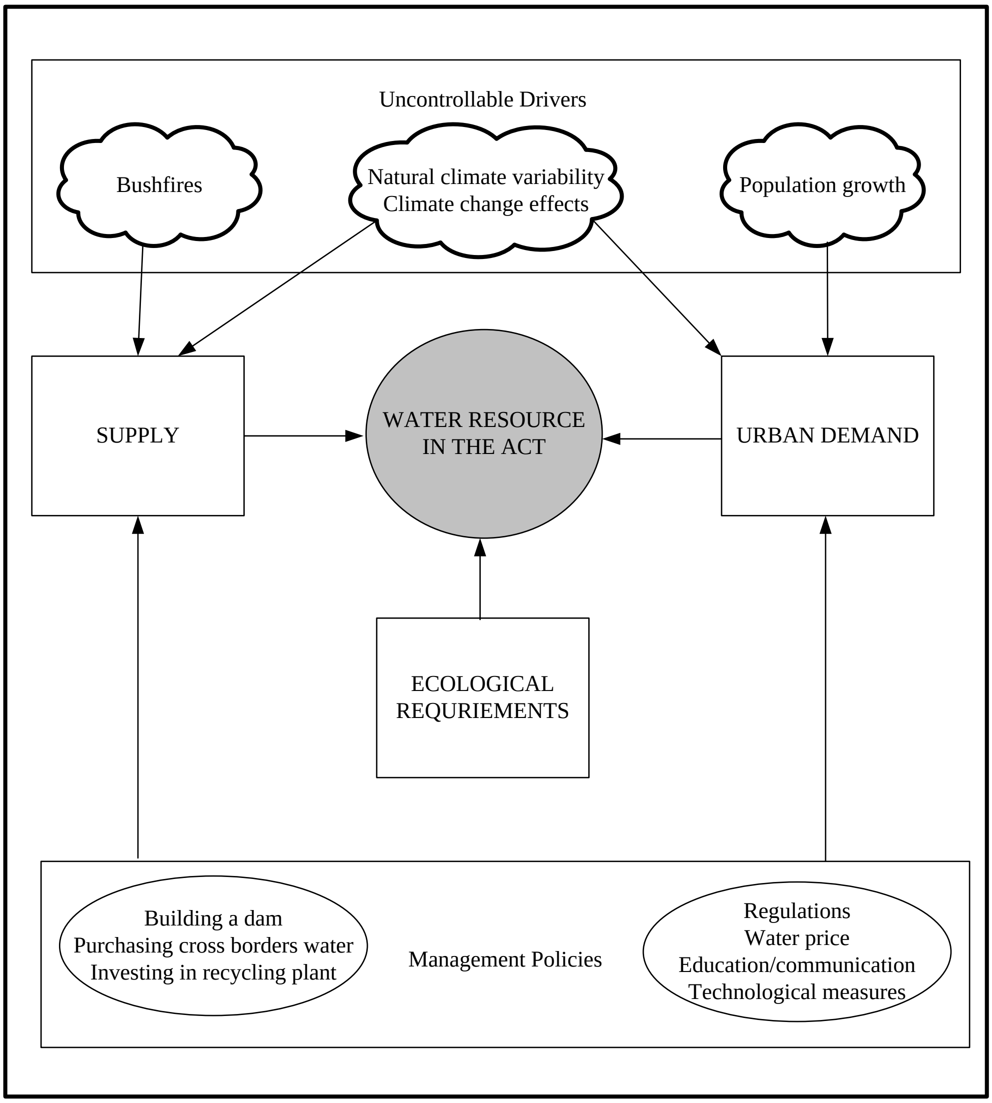

Figure 2: The preliminary model developed at the outset of the research

Eliciting Public Perceptions

Public perceptions constitute both a rich and legitimate problem representation (Garvin 2001). Ignoring public perceptions would have led to a very different model, one which could have been readily formulated. However, such an approach ignores the critical role that consumers' attitudes and perceptions play. Indeed, it is individual and collective perceptions that provide the basis for consumer behaviours. Understanding these perceptions is a critical enabler for effective public policies concerning water management. Without this there are significant risks of mis-communication: interventions found to be effective are most often preceded by a deep investigation of the audiences' existing knowledge and beliefs (Morgan, Fischhoff et al. 2002). Therefore, an important aspect f this knowledge elicitation task was to capture consumers' 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 consumer's cognitive map. A second session (20-30 minutes) was organized to validate the developed maps, refine language ambiguities and ensure consistent terms. Consumers 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].

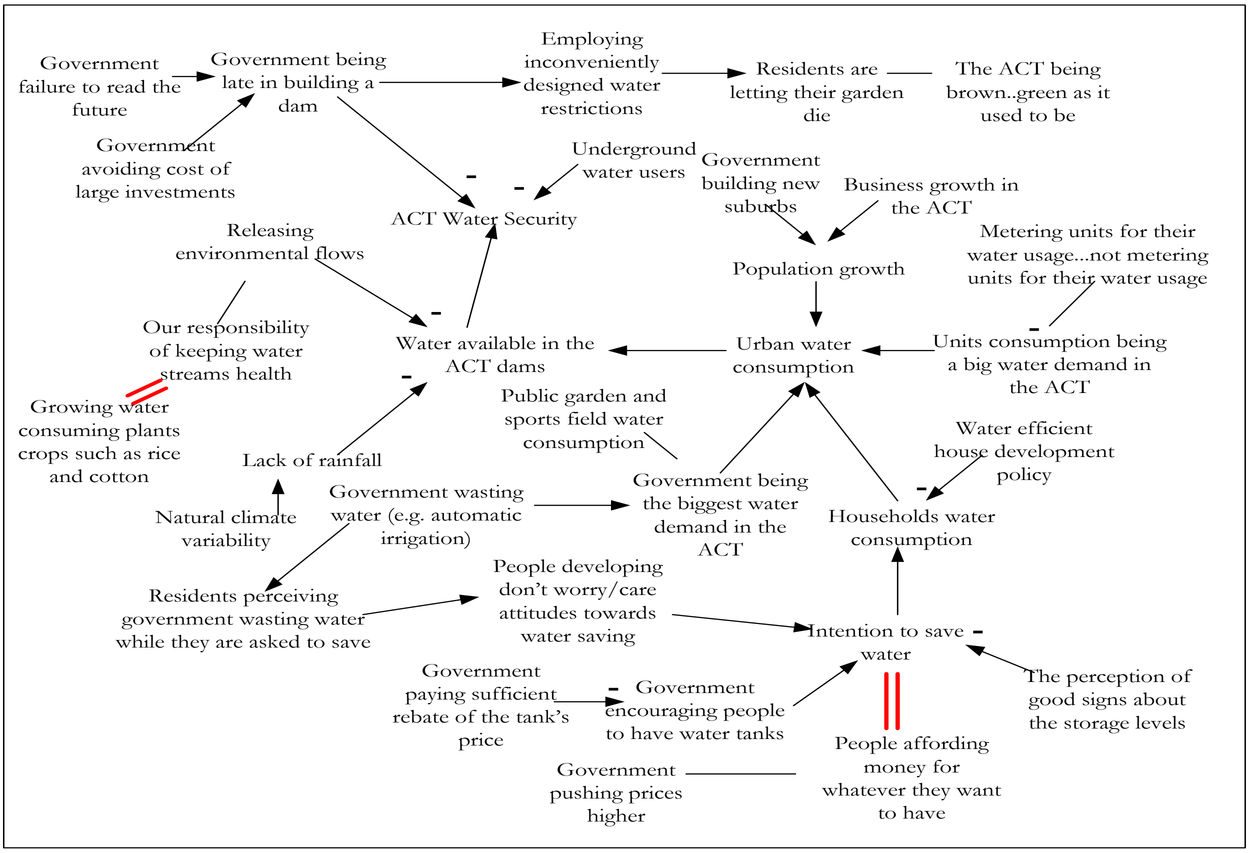

Figure 3: An illustrative example of a consumer's cognitive map.

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. In this research, managers denote those who work at strategic level to set up strategic and polices for managing both supply and demand. 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].

Perspectives in Water Resource Management

In [Step 10], we examined the structural properties of the cognitive maps. Analyzing the structure of the maps provides the basis for:

1. identifying perspectives that may emerge from the maps,
2. finding the most relevant or "nub of issues" that define the situation,
3. comparing between individual maps, and
4. converging towards a merged representation of the problem which represents those aspects of causality that are necessary to understand the dynamic complexity of the problem.

As a result, three perspectives have emerged from the analysis of the cognitive maps: hard, soft and expert's view. Figure 4 shows the key features of the three perspectives. In the hard perspective, the problem is framed as "insufficient water supply". The ultimate solution is to increase access to water sources by building infrastructure projects. Demand is given that needs to be satisfied. Gleick (2004) noted that the hard or technical view was the most dominant in the 20th century. Central to the hard view, development and growth are inevitable and favourable.

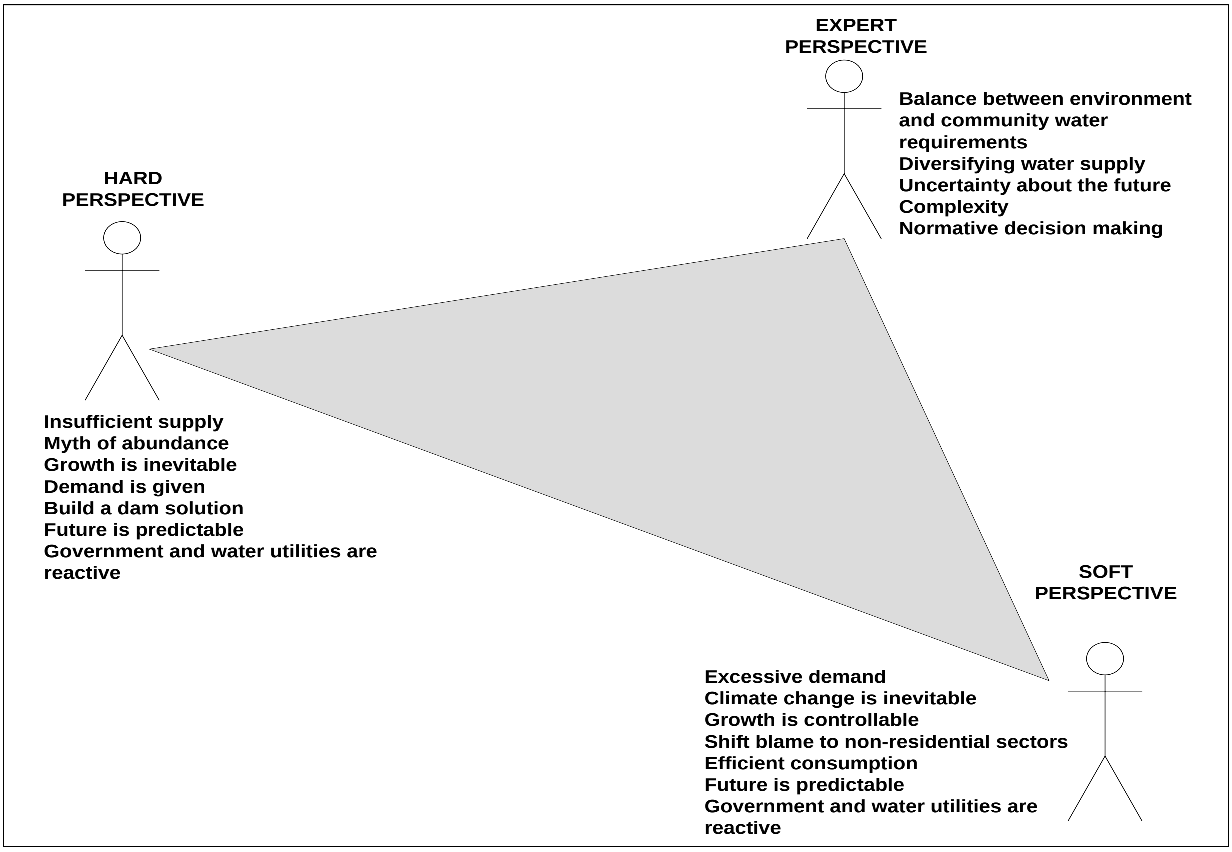

Figure 4: Key features of the three perspectives in water management

On the other hand, the soft perspective formulates the problem as "excessive demand" where efficient consumption seems as the most effective solution. The major difference between hard and soft view is rooted in the conflict between pro-development value (i.e. promoting expansion and growth) and anti-development (or limited development) values (i.e. promoting ecological integrity). While economic and lifestyle issues are major concerns to the hard view, environmental issues are critical to the soft view.

The expert perspective represents the viewpoint of policy makers in the ACT water utility. Central to this view, the problem is framed as "achieving balance between environment and urban water needs at short and long term”. Three interrelated concepts distinguish the experts’ view: trade-off, complexity and uncertainty. Policy makers constructed trade-offs, complexity and uncertainty as causes as well as challenges for effective management. In order to cope with these challenges, managers suggested that they had to continuously learn and adapt to environmental changes.

Building a Conceptual Model

The purpose of this [Step 11] was to create a conceptual model for the problem in order to:

a. model the knowledge and arguments discovered so far, merging the various views so that “synergy” and creativity become possible; and
b. focus understanding on the dynamics of the problem and the appropriate level of details for quantitative model building.

These representations (known in the literature 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). Whilst this step was to be part of the original methodology, focus groups could not be convened because of time constraints on the water resource managers. Alternatively, maps were aggregated and merged of maps by the research team, always remaining cognisant of the need to retain the diversity inherent in the original maps.

The conceptual model thereby created was a more refined and detailed version of the preliminary model (See Figure 5). First, the conceptual model provided an outline of the problem boundary and embraced the key hydrological, ecological and social processes that influenced the behaviour of water resource in the ACT. Second, it illustrated how issues in the problem context were abstracted to the modelling context. The conceptual models described the main features of the problem and modelling context in terms of fours elements:

1. drivers/scenarios,
2. pressures/scenarios leverage points,
3. system processes/causal structure, and
4. management interventions/policy leverage points.

Drivers describe the large-scale climate, ecological and socioeconomic forces or trends that drive changes in the system. Drivers exert pressures on the system whose direction and magnitude are sources of uncertainty or scenario leverage points in the model. System processes represent the hydrological, ecological and social processes that control the physical inflows and outflows to and from the ACT reservoirs. Management interventions are alternative policies that are used to manage supply and demand.

Designing an Electronic Format Elicitation Workbook

This step focused the analysis on those elements in the conceptual model on which participants did not agree [Step 12]. Our purpose was to scope the key variables and causal relationships which were candidates for quantitative modelling. The electronic workbook contained four 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 13] depicting the behaviour of the four variables. These influence diagrams provide the basis for building a SD model [Step 14].

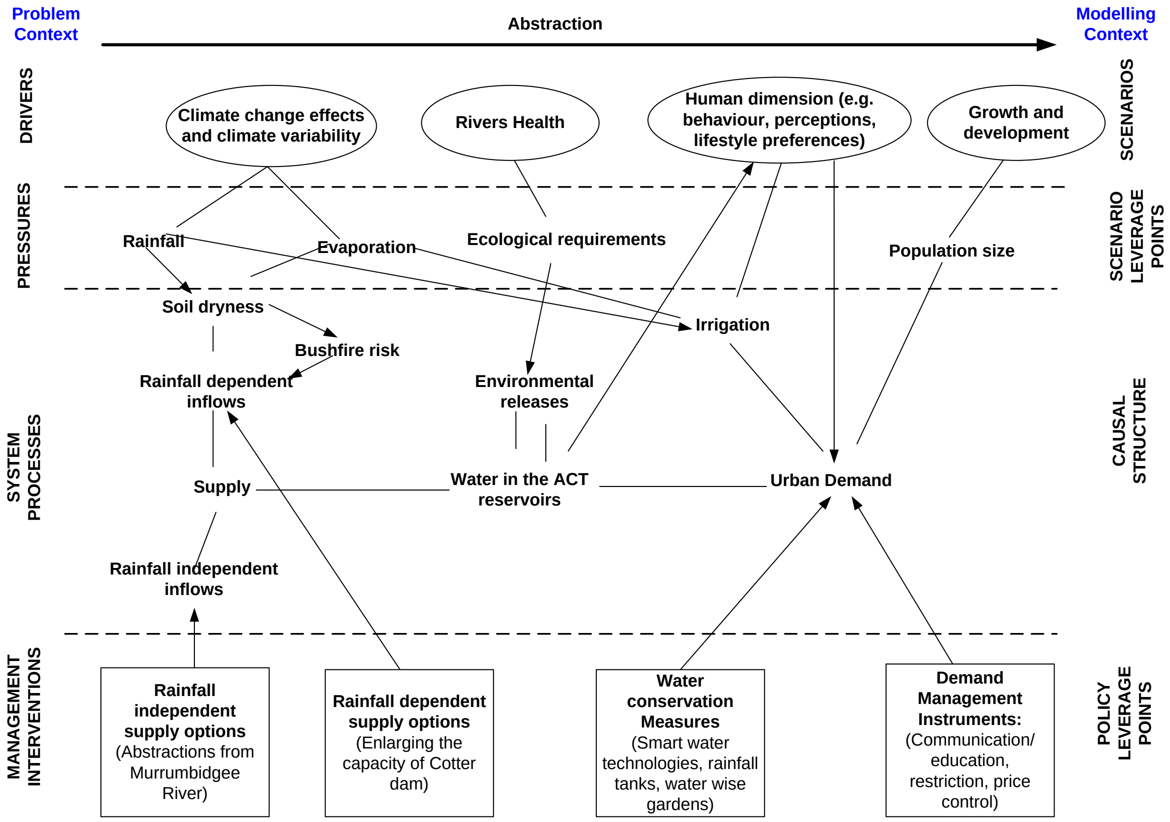

Figure 5: A conceptual model define the problem and modeling context

Building the Computational System Dynamics Model

The steps described above both reveal views of the problem faced by stakeholders and depict these as explicit causal mappings. These mappings will be re-visited later. Whilst these views and the causal relationships contained therein are conceptual in nature, they serve to inform the development of the computational SD model.

However, the specific causal structures and operating rules to be integrated into the construction of the computational SD model must take an algebraic form which necessarily represents a single and highly aggregated view of the problem. This view must be made explicit through the algebraic expressions based on the casual relationships between variables, and the variables themselves. These variables and the relationships between them also must be quantifiable. An inevitable consequence of building of the computational system dynamics model demands working at a higher level of aggregation, taking a top-down casual view within the context of a defined problem boundary. The causal structure of the problem, expressed as a highly-aggregated system dynamics influence diagram is shown at Figure 6.

The influence diagram depicts, *inter alia*, the presence of seven interacting feedback loops. The limit of human cognitive capability in dealing with feedback is characterised by a single first-order linear feedback loop (Sterman, 2000: McLucas, 2001). Hence, the dynamic behaviour arising from the causal structure inherent in Figure 5 is certain to confound our unaided human cognitive capability. Here we call on computational SD modelling to aid our understanding of the feedback dynamics.

The main challenges in the building of the computational SD model arose in quantifying the large number of variables involved and the causal relationships that link them together. Each of these had to be validated. Model functionality was verified and behaviour validated (as far as is possible with SD models) using techniques drawn from proven systems engineering methodology (Blanchard and Fabrycky, 1981; Faulconbridge and Ryan, 2002).

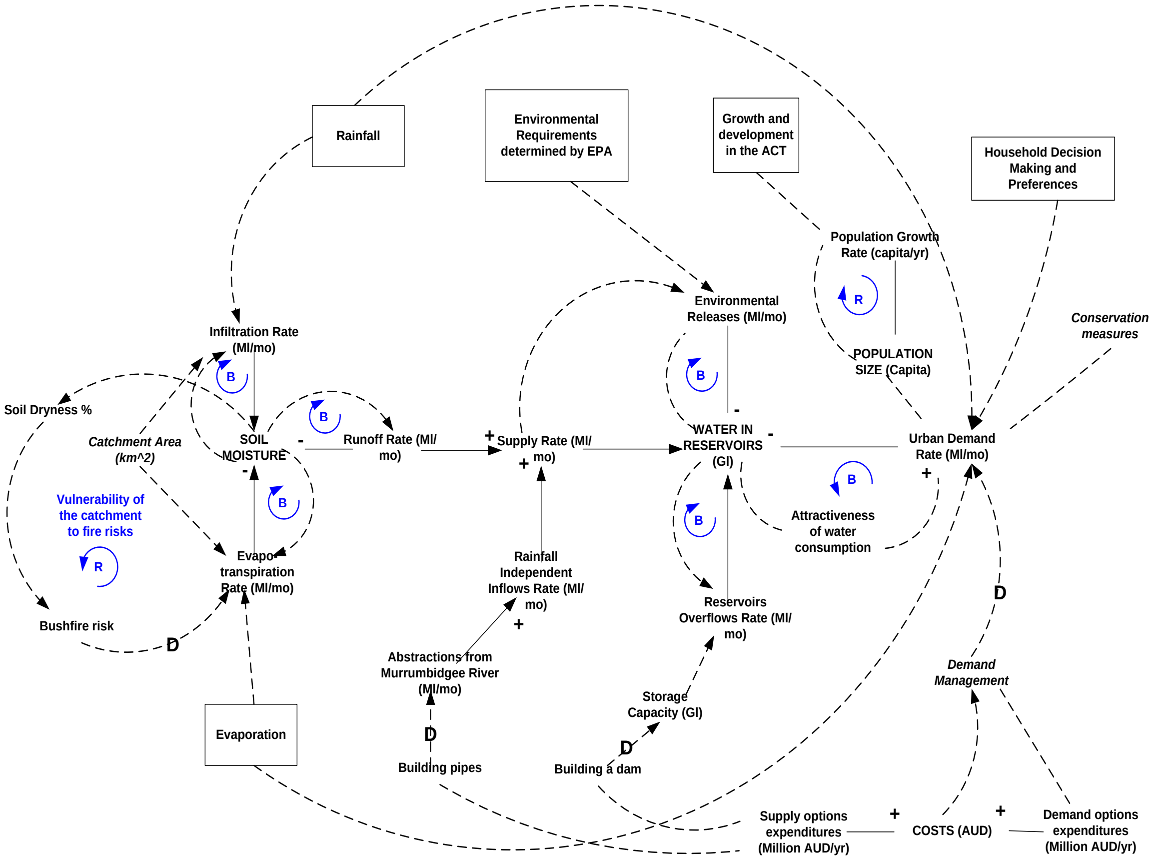

Figure 6: An aggregate level influence diagram of the problem structure

Model Verification and Validation

The model was constructed using a modular approach. Each module represented a sector in the problem. The supply and demand sectors were tested separately, compared with historical behaviour reference modes before being linked. Figure 7 shows the behaviour produced by the model in representing accumulation in the reservoirs over a period of 20 years compared with the actual historical time-series data.

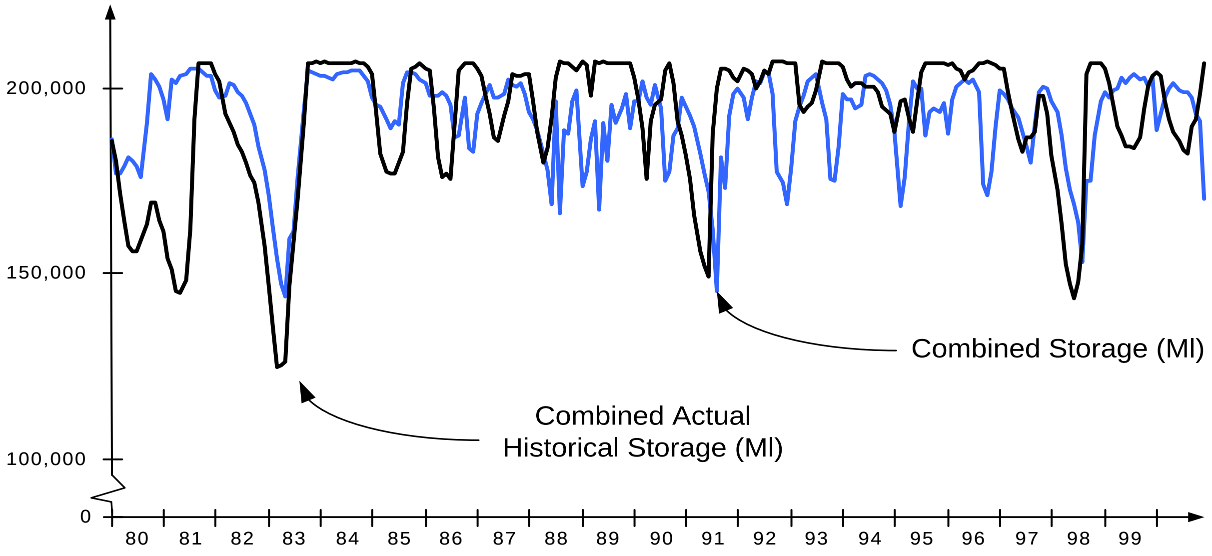

Figure 7: Comparison of Actual and Modelled Behaviour – Combined Water Storage

Development of a Management Flight Simulator

Whilst the system dynamics model is complete, the simulation game is yet to be developed and its effectiveness in facilitating the growth in understanding by customers and managers is yet to be tested. However, some important lessons have already been learned. First, the process has reinforced a number of lessons learned by SD modellers over the years, and second, the process has exposed a significant number of mis-perceptions about water security among supply managers and the consuming public: these are discussed in the next section.

Discussion and Conclusions

This research presents a practical application of using multi-methodology to investigate wicked problematic situations, such as water sustainability in the ACT. The application combines the use of soft systems thinking technique (i.e. cognitive mapping) and hard systems thinking techniques (i.e. SD and scenario analysis) in a transparent process which cascades from subjective maps, to qualitative causal models, then quantitative dynamic models. The application demonstrates that applying multi-methodology has strengthened the inquiry process in various ways:

1. Multi-methodology has provided multiple lenses for investigation various sources of complexity and uncertainty that are inherent socio-ecological systems:
    a. Cognitive mapping has been effectively used to explore the social and cognitive aspects of water issues. The findings of the empirical study have given the researcher an appreciation of the situation as perceived and expressed by the actors in the problem space (i.e. water users and managers).
    b. Qualitative and quantitative causal analysis are used to improve understanding of the dynamic complexity of water resource and the causal structure that endogenously generate the behaviour of water supply and demand in the ACT.
    c. Scenario analysis has provided an effective vehicle to examine the dynamic coherence of various views about water resource, and to communicate about sources of uncertainty.
2. The cascading process has provided a transparent process where the modelling assumptions, model structure and input are clearly spelled out. This design contributes to:
    a. an on-going validation and inconsistencies checking,
    b. improving credibility and confidence in modelling output,
    c. exposing the modelling process for external review, and
    d. facilitating future use of the modelling results.

This section discusses some of the insights that have been gained through the modelling process.

In the Getting Started Phase.

This research was motivated by the researcher's perception of the opportunity to improve communication about water resource in the ACT. To start the project, it was essential to establish a relationship with the water utility company in the ACT (i.e. the client).

In the first phase of the project, the researcher initiated a dialogue with the client to explore avenues for linking efforts and collaborating.

The following insights are drawn from this phase:

1. In some cases, managers (i.e. potential clients) are not aware of the potential of modelling (i.e. especially qualitative) in addressing the problems they face. In such cases, modeller-initiated project may be very effective.
2. To create a point of entry and gain client's commitment, the researcher has to formulate research questions that are closely linked to management questions and issues of concern.

3. The use of a preliminary model is useful in broadly characterizing the issues for investigation. This helps facilitate communicating with the client at the early stages of the analysis.
4. In this early stage, it is useful to avoid drawing speculative or premature causal assertions about the problem.

In the Cognitive Mapping Phase

1. Cognitive mapping is highly effective technique in:
    a. building a rich and multi-perspective understanding of the problem,
    b. framing the ``nub of issues" that define the situation,
    c. empirically validating the initial argument about the perceived limitations of the employed policies for communicating about water resource;
    d. eliciting the salient decision rules that govern decision making of users and policy makers;
    e. identifying barriers to engaging in water saving, and hence, communication targets, and
    f. eliciting modelling requirements.
2. Constructing perspectives is a quite challenging process because:
    a. It is much difficult to distinguish between the rules that actually govern interviewees' decisions (i.e. theories in-use) and what they say/think about the rules that influence their decisions (i.e. espoused theories). The use of semi-structured interviews is useful in deeply investigating the salient factors that influence decision making.
    b. It is very cognitively demanding task to make sense of such large set of data and synthesize results to extract higher-level perspectives.
    c. The mental models included aspects of more than one perspective, which can be interpreted as internal conflict. In such case, it became difficult to distinguish between conflicts within one frame and conflicts that cut across multiple frames.
    d. Despite significant effort, some of the researcher's biases and preferences inevitably influence the process of constructing frames.
    e. The use electronic template, like the one designed in this research, provide an effective tool to validate large-size cognitive maps, for time-stressed participants. However, it allows only for validating relationships that are already identified rather indicates if there are relationships which are missed out.

In the Cognitive Mapping Phase

1. The flow from the conceptual model to the influence diagram is not a smooth linear transition. Some feedback loops have not been directly inferred from the cognitive maps. Still the modeller has to investigate and identify missing feedback loops, which was effort and time consuming task. This process can be substantially facilitated by the use of Group Model Building sessions where participants directly contribute to building the dynamic hypothesis
2. It is essential for modellers to master different causal mapping techniques, be aware of their strengths and weakness, and to smoothly translate the dynamic hypothesis from one form to another dependent upon the purpose. In the research, Coyle's influence diagram is used as a conceptualization tool because it imposes a rigorous and systematic consideration of the variables and their interrelationships. Whilst influence diagrams is not easy to communicate especially with non-technically trained people, influence diagrams are better kept in the ``modelling kitchen" while CLD is used as an interface with the client.

3. It is useful not to wait till the dynamic hypothesis is completely finished to start building the stock-and-flow diagrams. The transition back and forth between influence diagrams
   a. provide an early test for the logic of the dynamic hypotheses;
   b. identify vague concepts, contradictions and inconsistencies;
   c. improve understanding about causal links and their mathematical representation;
   d. provide insights into missing variables that were necessary for the inner working of the quantitative model; and
   e. spotlight quantitative data requirements

In the Model Formulation Phase

1. SD is a powerful technique for modelling the dynamics of hydrological process. Relatively ``simple" and less data-intensive rainfall-runoff model generates results that confirms with sophisticated simulation models. This argument is also supported from feedback of hydrologists who have participated in validating the model performance.
2. In the closure session of the 27th System Dynamics Conference, in Albuquerque, Professor John Sterman gave a talk about his Climate Change based C-Roads model and future directions to extend the model. After the talk, an audience asked Sterman about why he is looking to extend his model if the more simple the model is the more learning insights can be gained. In concise words, Sterman answered that although the bathtub metaphor (i.e. one stock, one inflow and one outflows) is sufficient to model the dynamics of the system, it is not sufficient to convince actors to change their mental models about the system. This summarizes the modelling paradox the researcher muddled through to select the model's granularity (i.e. resolution or level of details). The question is how to develop a parsimonious model that sufficiently includes the requisite variety necessary to address the problem. In practice, learning to be simple is more difficult to do than to say especially that young modellers may have over-tendency to add and connect variables. To help overcome this dilemma, it is very useful and time efficient to follow a systematic process, such as the Systems Engineering “VEE” model (McLucas, 2005). Based on the modelling requirements identified in problem structuring, the “VEE” model has guided an incremental model development process where:
   a. The model starts as a highly aggregate representation (i.e. bathtub and basic flows).
   b. In a top-bottom fashion, the model is broken down into a series of modules at which every module is built, verified and documented. This includes checking consistency with previous modelling artefacts (i.e. conceptual model and influence diagrams). In case a variable does not appear to have a reference point, it is further scrutinized to make a judgement whether it is necessary or should be dropped. The reference modes are used as guidance. If the variable does not contribute to generating the reference modes, then it is excluded unless it is essential for deploying a model requirement.
   c. In a bottom-top fashion, modules are incrementally integrated and verified.
3. Maintaining a continuous modeller-client dialogue is critically important to share results, resolve problems and review assumptions. This helps to improve modelling credibility and quality. The client participated in reviewing model assumptions and testing its performance. Moreover, the client shared their experience in demand modelling and provided a demand prediction tool which was incorporated into the model.

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