Water Accounting System for Strategic Resource Management

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EXTENDED ABSTRACT

This paper describes a water accounting system (WAS) that provides a strategic long-term water management tool. The WAS integrates water use and availability, provides a comprehensive and consistent historical database, and allows exploration of scenarios. The WAS has spatial, temporal and sectoral resolution and has been established and tested for the state of Victoria in Australia, and can be extended to cover other or all regions of Australia. It is part of a larger stocks and flows framework covering key drivers such as demography, land-use and electricity production.

The WAS has features in common with system dynamics, such as the evolution of stocks (with age profiles), linking of stock and flow variables in causal chains of influence, and the use of a diagrammatic interface and time series output. However, an innovative difference of the present work with system dynamics is the deliberate removal from within the model code of feedback loops that involve choices belonging to the social or economic domain. This has particular importance for stimulating and exploring the many behavioural, technological and engineering options that are possible for resolving tensions between, in this case, water supply and demand. In particular, it is possible to arrange the information flows, as shown in Figure 1, which allows influence chains to be traced so that the main causes of tensions can be readily identified.

This paper demonstrates the advantage of taking this “design approach” implemented in the *whatIf* software environment for understanding the complex interactions in, for example, the water system and identifying key drivers of long-term (50+ years) sustainable futures. For example, Figure 2 shows the river flow in the catchment that supplies the majority of water to Melbourne. Both historical data and two scenarios are shown. The scenarios are for a high climate change environment (average global temperature increase of 2.2 °C in 2050). River flow drops rapidly and ceases in 2100 if increasing proportions of river flow are diverted to maintain the Thomson Reservoir at about 50% capacity. Less pressure is placed on the river if extra proportions are not diverted, but the Reservoir fails in about 2040.

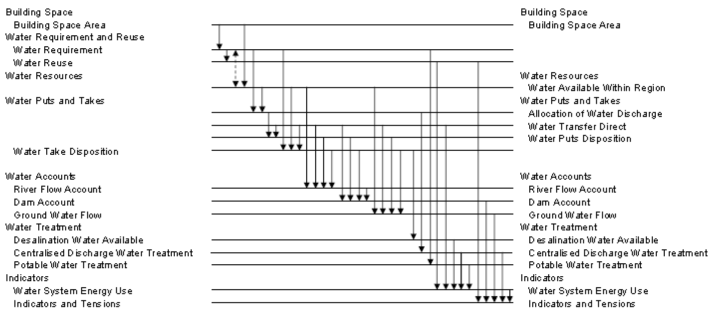

Figure 1. Data flow between modules of the WAS, arranged to emphasis those components of that receive data.

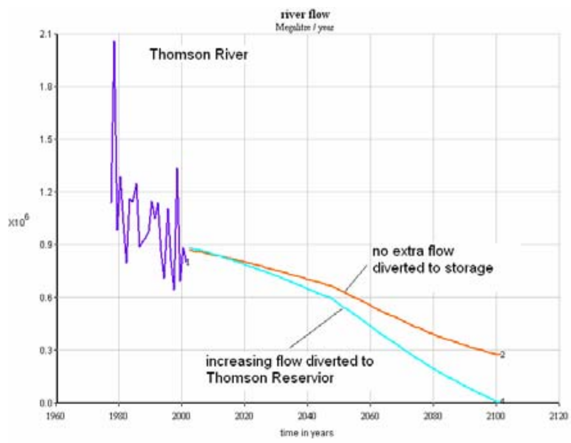

Figure 2. River flow in the Thomson River, covering history and alternative management scenarios under high climate change.

Many other water management options and scenarios can be created and explored in the WAS. Ideally, this would occur with the engagement of key stakeholders. It is beyond the scope of this paper to document this process or a range of scenarios.

1. INTRODUCTION

Management of water resources throughout large areas of Australia has become a major challenge in recent years. Serious drought has occurred for several years throughout eastern Australia from Queensland in the north, through NSW, to Victoria in the south; and there has been long-term decline of rainfall in SW Western Australia. These conditions have affected agricultural production while also impacting significantly—perhaps for the first time—the water security of Australia's major urban areas where the vast majority of Australians live. Water restrictions have been introduced in the capital cities—Brisbane, Sydney and Melbourne—where major storage levels have decreased to levels that may support the cities for only one year without further rainfall.

The discussion of these water constraints has involved a wide range of views about causes and possible responses. These include:

- the contribution of possible climate change to reduced water availability;
- the role of water pricing and trading in improved allocation of water, including for environmental flows in rivers and wetlands;
- comparisons of broad options for providing future water security of capital cities, such as acquisition and transfer of water previously used in agriculture, or engineering and technological options such as desalination, recycling and constructing new dams;
- conflicts of management responsibility between State governments particularly in the Murray-Darling Basin which spans the four States of Queensland, New South Wales, Victoria and South Australia – and the role of the Federal government in managing water resources.

Amid the discussion it has become evident that information and understanding about the water system is insufficient to support evidence-based decision making. Part of the response has been the launch by the Federal government of a National Water Initiative.

The water account system (WAS) reported here uses a stocks and flows framework and is designed to help identify causes of water constraints and possible responses within a strategic long-term perspective. It addresses questions relating to the natural and built water system and to the demand for water, and how this relates to the rest of the economic activity in Victoria. The WAS effectively integrates the data from the static water accounts (of the National Water Commision (SKM, 2006) and the Australian Bureau of Statistics (ABS, 2006)), as well as other historical data over previous decades, and allows quantified scenarios over future years, out to 2050 and beyond, of the water system to be created and analysed.

While the approach of this stocks and flows framework (SFF) WAS has features in common with system dynamics, a primary difference is that feedbacks that essentially relate to choice (social behaviour including economics and choice of technologies) are not hardwired in the SFF. Instead, the SFF WAS tracks the physical cause-and-effects while providing multiple inputs for the vast range of choices that are possible in managing the long-term future of the water system – a "Design Approach" (Gault 1987) to the management problem, which is implemented in specifically designed "whatIf" ® software (Hoffman 2005). Our approach rests on the understanding of the physical importance of resource based systems, and allows for economic reaction or institutional guidance or any other management construct to be implemented in response to the physical system and aims of society.

2. OVERVIEW OF THE FRAMEWORK

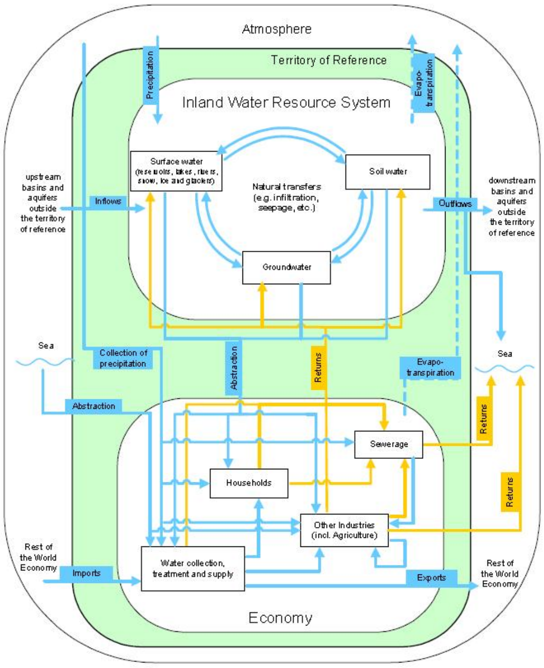

Figure 3. The main flows of the United Nations framework (2007), are tracked in the WAS.

This water accounting system effectively partitions the water that is naturally available and the water that is required by all economic activity within the

State into the various water body types and water regions. It tallies up the availability and the requirement so that tensions can be observed in the river, storage and groundwater systems.

The coverage and level of detail of the WAS closely matches that of the physical account of the System of Environmental-Economic Accounting for Water (SEEAW) framework developed by the United Nations Statistics Division (2007) (see Figure 3). The current version of the water account framework covers:

- water requirements across all sectors of the Victorian economy (informed by other components of the SFF) at local government level, including:
    - water recycling by centralised treatment plants;
    - re-use of water (within industry or sector)
- water availability by 29 water regions (see Figure 4), influenced by many factors, including:
    - climate variables;
    - land-use (informed by other components of the SFF)
- water stocks or flows:
    - surface (rivers, wetlands);
    - storage (dams);
    - soil (groundwater/aquifers);
- water discharge from all water uses, tracking water quality by:
    - unpolluted;
    - blackwater;
    - greywater;
    - stormwater
- water transfers between water regions and inter-State;
- additions to and extractions from (i.e., puts and takes of) all water stocks, by:
    - centralised systems; or
    - self-extracted means
- energy required to treat and move water for:
    - potable treatment and pumping;
    - sewage treatment and pumping;
    - desalination;
    - inter-region transfers

The spatial coverage of the framework is the state of Victoria, with the accounts maintained in each of the 29 water regions of Victoria (see Figure 4). Appropriate geographical connections such as transfers between states are also included. The water regions are major catchment basins, and are linked in the framework according to the river networks.

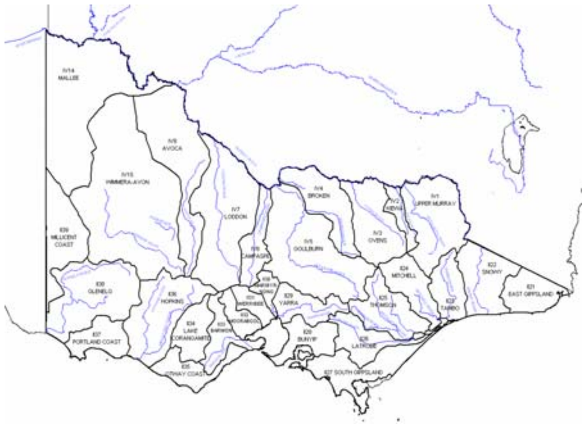

Figure 4. Victorian water regions used in the WAS. The major rivers are displayed, including those entering the Murray River along the northern boundary of Victoria.

The framework simulates in 1-year time-steps. Other time-steps (e.g., monthly or seasonal) or spatial resolution could be developed if required. The suitability of spatial resolution and time-step is related to the intended purpose of the simulation, as described below. Some measure of water quality can also be presented due to water use and treatment, as set in the framework.

The water account is not a hydrological model as such, but more an accounting procedure. This is most simply demonstrated by the possibility of temporarily creating negative volumes of water – a physical “tension” that must be resolved by people interacting/using with the framework. No assumptions or optimisations are made within the framework about how various tensions are to be solved; instead, those using the framework can trace back to the various causes of such tensions and explore many of the alternative ways to resolve these.

The water account considers only the aggregate water bodies in each water region—smaller area hydrology is not modelled explicitly since this can be done by others while using the water account to understand critical drivers and determine strategic water management directions.

2.1. System Dynamics Features

Stocks and flows are a key feature of the WAS, as illustrated in the “Dam Account” module. Figure 5 shows part of this module, demonstrating the use of flows (shown as pipes), stocks (barrels) and parameters (hexagons). In this excerpt, the level of water storage (dam volume) is the stock calculated on the basis of all flows to and from the dam: evapouration losses, balance of piped extractions and additions (net dam puts), water diverted from the river system, or water released into the river from storage. The calculation integrates these flows over time, starting from a base level at the beginning of the scenario.

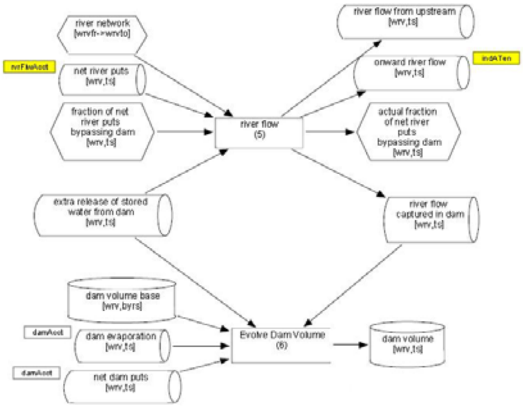

Figure 5. Excerpt from the "Dam Account" module of the WAS.

A more complicated calculation included in Figure 5 involves the river flow along any potential network. The diversion of water from the river into the storage is specified by a net by-pass fraction, which is the proportion of the river flow in the river basin that is not diverted to storage. The flow that remains in the river exits the region, and may enter another region if there is a river network connecting them, as there is for the northern basins along the Murray River (see Figure 4). Calculation of diversions to storage further down the river network account for this cumulative flow and take advantage of the matrix mathematics that is available in the whatIf software. The river network is specified efficiently using a vector (1-dimensional matrix) that has as its elements the combinations of regions that are connected by river water flows e.g., the head water region (IV1 or Upper Murray) is connected to all the lower regions along the Murray River. This vector is converted to a two-dimensional matrix, which is used in the calculation of the cumulative river flow. Modelling a different river network is simply a matter of creating a new vector.

2.2. Design Approach Features

The structure of the water account reflects the “demand-supply” separation of the “Design Approach” (Gault, 1987). Information on the modules that make up the WAS, and some of the many links between them, is given in section 3. The supply of and demand for water are specified separately. Supply is primarily determined by the ‘water availability within region’ module while demand is largely specified by the ‘water requirement’ module. This is illustrated in Figure 6 where data flows are indicated by arrows – data flows on the right side of the diagram relate to supply and those on the left to demand.

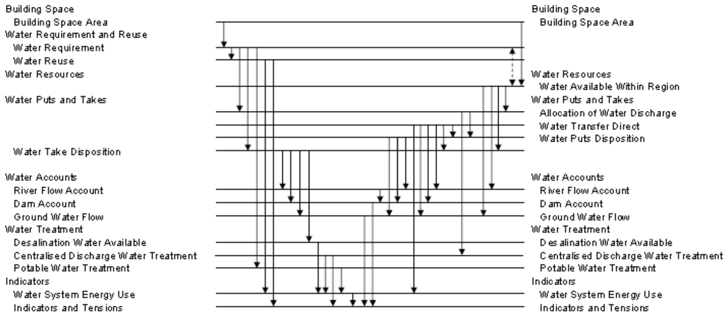

Figure 6. Data flow between the framework modules, organised according to components supplying data. Arrows on the left are generally associated with data about demand for water, those on the right with supply.

As noted above and suggested by the separate specification of demand and supply of water illustrated in Figure 6 it is possible to produce conflicts or tensions between the demand and supply. These tensions may even result in physically unrealistic results, such as negative dam volumes. Tensions are manifested in lower modules, especially the ‘dam account’ and ‘ground water flows’.

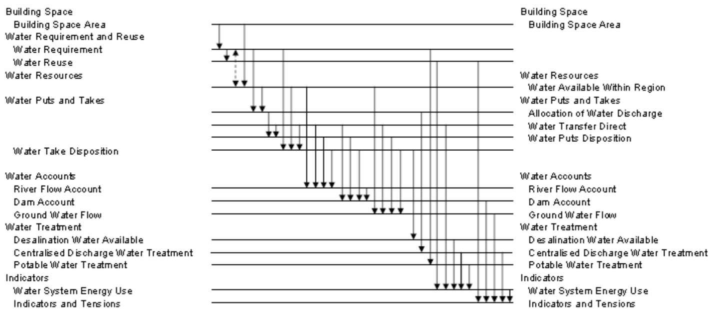

Figure 7. Data flow between framework modules, organised to emphasize those components of the water account that receive data.

The water account framework does not directly incorporate a means for resolving the tensions; instead it is intended to facilitate a variety of solutions to be designed and compared. These solutions may involve engineering projects (e.g., greater dam capacity), technological innovation (e.g., water recycling) or behavioural or structural change (e.g., less water use).

The structure of the data flow within the framework is a key feature for facilitating understanding of the water system and creating solutions to tensions. This is illustrated in Figure 7 where the cause of tensions that are collected at the bottom of the diagram can be traced back up through the framework.

In addition to manually resolving tensions, supplementary scripts can be written in the whatIf software application. These scripts can simply display collected or manipulated outputs, or they may be written to enter data into the exogenous variables. A combination of these scripts can be used to form feedback loops that resolve tensions, such as maintaining dam levels by adjusting diversions and extractions from the river network.

2.3. Calibration

These frameworks are calibrated over several decades to reproduce a wide range of historical data sets (Baynes 2007). This provides a high degree of confidence in the simulation due to the wide variation in value of some inputs (e.g., rainfall), the multiple ‘cause and effect’ chains influencing output variables, and the fact that we reproduce output variables (e.g., storage levels and energy used in the water sector) simultaneously. It also means that all variables have historical data which provides context for understanding past changes, and the foundation for creating meaningful scenarios.

3. SOLVING TENSIONS

A good way to explain how the water account works is to describe a flow of primary data connections starting from a key *endpoint* of the account, such as the water storage level of a water region. This approach is useful because there are so many potential alternative influences on endpoints of the account, so that it is easier to understand by working back from the endpoint variable, through the various branches of influence.

Briefly, the total water storage level within a water region is determined in the “Dam Account” module by the amount of river flow that is diverted to this storage, evaporation losses from the storage, and the balance between the other “puts and takes” from the storage. Therefore, if there is a problem or “tension” in the storage level—either being too high or too low (including a storage level that may be greater than the storage capacity, or a level less than zero)—we can look at several options for alleviating this tension. This is illustrated in Figure 8, where a high climate change scenario has been incorporated with other scenario settings (Turner 2007) for the economy and society in Victoria. If the proportion of the Thomson River that is diverted to storage is kept constant, then the storage level falls precipitously after about 2010 and becomes negative after 2040 (orange curve of upper graph in Figure 8).

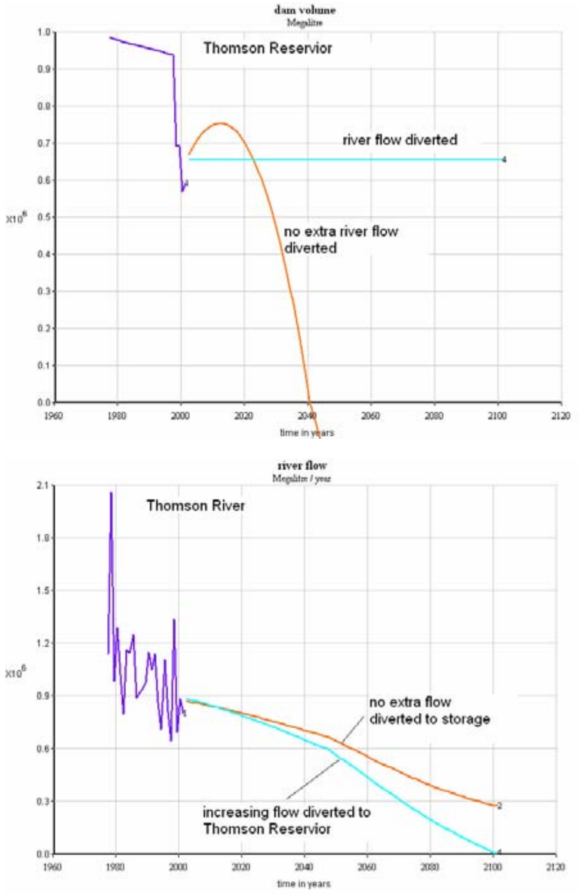

Figure 8. Water storage level (top) for the Thomson Reservoir, over past decades and for two alternative scenarios; and corresponding river flows (bottom) in the Thomson River.

One option to alleviate this tension is to adjust the amount of water diverted from the river system of the region to the storage (aqua curves of Figure 8). This clearly has an impact on the river flow, decreasing the average flow to zero by the end of the century. The tension has been shifted from the stock variable (storage) to the flow, not only in that region but also in any downstream regions. The river flow through the network of water regions is influenced by all other puts and takes from the river system. The balance of these puts and takes is set out in the “River Flow Account” module.

An alternative option to using the river system to manage storage levels is to examine the puts and takes that occurred directly to and from the water region storage. All of the puts and takes from both the river and storage system (and groundwater) are collected together in two separate modules: “Water

Puts Disposition" and "Water Takes Disposition" modules. These modules simply describe, within each region, the choice of water body type (rivers, storage, or groundwater) for each extraction or addition.

Similarly we may choose to move water from a water body type in one region to any other water body type in any other region, as set in the "Water Transfer Direct" module. Such transfers also contribute to the puts and takes accounting. Water transfers include those made to and from Victoria.

Apart from the transfers, the total volume of water puts is determined by the amount of water that runs off the built environment or that is discharged from any type of economic activity. Stormwater running off the built environment is calculated from a combination of the rainfall and land use accounts, in the "Water Available Within Region" module. The discharged water is determined from the amount of water that is not consumed, or treated to become available as cleaner water, in the "Allocation of Water Discharge" module.

The total of the water consumed, discharged, or treated is the volume of water required by all economic activity within each water region. This volume is tallied up from all the separate economic activities in the "Water Requirement" module. Any water reused by a particular activity is accounted for (by reduced water intensities used in the Input-Output tables of the "Material and Energy Transformation" module elsewhere in the framework).

The volume of water required throughout the economy is used to inform the amount of water takes, after allowing for possible water supply from desalination and from the roof-water systems. Roof-water interception, like stormwater, is determined in the "Water Available Within Region" module. This module also determines whether rainfall within a water region is evapo-transpired, runs off as surface water, or goes to groundwater, based on hydrological variables and the land use accounts obtained from elsewhere in the framework.

Other calculations also take place within the water account. For example water loss associated with the transfer of water between water regions either by pipes or canals is included. Also, the amount of energy required to reuse and move water, and to treat water of different quality is calculated. The energy required is totalled and then aggregated with all other electricity requirements of the Victorian economy elsewhere in the framework.

Flows of water to and from the groundwater system are collected together in the "Ground Water Flow" module. The balance of these flows can be compared with estimates of the sustainable yield of the groundwater system, and the comparison reported as another tension. While it is possible in principle to model the stock level of the various groundwater bodies we have not included this in the present accounting system at this stage since the current understanding of the interactions between various groundwater bodies and other water types is very poor.

4. DISCUSSION

4.1. Comparison with Other Accounts

Assembling water accounts is a relatively recent activity in Australia and other parts of the world. Domestically, a water account undertaken by SKM for the National Water Commission (SKM, 2006) provided data on the natural water system in its current state. The SKM account does not cover water use in any detail, but compared with the WAS it has categories for more detail on groundwater stocks and small-scale storage (e.g., farm dams). Complementing the NWC account are the recent water accounts produced by the Australian Bureau of Statistics (ABS), which focus mainly on the use of water (ABS, 2006), with sectoral detail also categorised by how the water is obtained (e.g., self-extracted, distributed, etc.) and discharged. Little information is provided on the availability of water associated with the natural system, in contrast to the WAS.

While these two approaches are useful, they are limited in their contribution to water management because of two shared features:

- by focusing mainly on either supply or demand of water they fail to provide an appropriate system perspective; and
- by supplying current data they provide at best for short-term adaptive management and fail to provide understanding of the pressures and dynamics that is needed for decisions involving long-lived infrastructure and effects on the water system.

The WAS described here spans both natural and human water systems, and provides the dynamic capability for historical analysis and scenario exploration. Its coverage and level of detail closely matches that of the physical account of the System of Environmental-Economic Accounting for Water (SEEAW) framework developed by the United Nations Statistics Division (2007). The main flows (and others) of SEEAW (see Figure 3) are captured in the WAS.

4.2. Water Quality

The current framework does track the volumes of water of different quality (clean, storm-, grey-, and black-water). Consequently it is possible to construct measures of overall water quality based on relevant ratios of these volumes, such as the percentage of discharge water that makes up the overall river flow volume. Nevertheless, water quality modelling is not the central focus of the present modelling in the WAS. This reflects the fundamental importance of water quantity for sustainability, and that water quality makes additional imposts on sustainability assuming adequate volumes of water are available.

4.3. Resolution

The question of resolution relates to the purpose of the model or simulation. In this case, we are interested in exploring long-term scenarios to 2050 and beyond. Over this timeframe the potential growth in demand for water, and the potential impact of climate change, are much bigger factors in how the water system is maintained and operated than other hydrological details. Consequently, the 1-year time-step and river-basin resolution are most appropriate for the WAS. This level of detail is also recommended by the UN for water accounting (in the SEEAW framework).

Nevertheless, substantial variation in rainfall is a feature of the Victorian (and Australian) climate system, and other changes may similarly involve large fluctuations or variations in the future. Any potential non-linear effects can be incorporated in the relevant exogenous control variables, such as the partition of rainwater between surface flows, groundwater and evapo-transpiration. Such information may be derived from more detailed models, expert advice or empirically. Indeed, the historical calibration of the WAS demonstrates that empirical settings of control variables can be determined so that observations of a wide range of human and natural water system variables are reproduced.

5. CONCLUSION

A water accounting system (WAS) has been developed that covers both the natural and human elements of the water system. This WAS draws on features of system dynamics, complementing this with a "design approach" structure. This means that 'what if' scenarios can be created and explored, and most importantly, key drivers of the water system can be identified via chains of 'cause-and-effect'. The WAS has been applied in the state of Victoria, where it was calibrated to reproduce a wide range of historical observations.

This application illustrates some of the potential for the WAS to address issues relating to water constraints and possible responses, as noted in the Introduction. Climate change is evidently a potentially large and dominating factor in water futures. While the WAS does not involve prices, it does present the physical implications of different allocations (but not explored in the illustrative scenarios above). Other work being reported explores broad options for providing urban (Melbourne's) water, using the WAS (Kenway 2007). The data coverage of the WAS could be extended beyond Victoria (ideally, nationally) to analyse inter-State management options, rather than having to use exogenous inputs.

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