HISTORICAL CALIBRATION OF A WATER ACCOUNT SYSTEM

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Socio-Economics and the Environment in Discussion
CSIRO Working Paper Series 2009-04

March 2009
ISSN: 1834-5638

CSIRO

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Historical Calibration of a Water Account System

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ABSTRACT

Models that are used for future based scenarios should be calibrated with historical water supply and use data. Historical water records in Australia are discontinuous, incomplete and often incongruently disaggregated. We present a systematic method to produce a coherent reconstruction of the historical provision and consumption of water in Victorian catchments. This is demonstrated using WAS: an accounting and simulation tool that tracks the stocks and flows of physical quantities relating to the water system. The WAS is also part of, and informed by, an integrated framework of stocks and flows calculators for simulating long-term interactions between other sectors of the physical economy. Both the WAS and related frameworks consider a wide scope of inputs regarding population, land use, energy and water. The physical history of the water sector is reconstructed by integrating water data with these information sources using a data modelling process that resolves conflicts and deduces missing information. The WAS allows strategic exploration of water and energy implications of scenarios of water sourcing, treatment, delivery and end use cognisant of historical records.

Keywords: water accounting, stocks and flows, historical time series, data modelling, calibration

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INTRODUCTION

Australia is urgently seeking solutions to problems of water security in the context of climate change and capacity constraints. According to the Department of Sustainability and Environment, Melbourne (DSE, 2004b), “if Melburnians continue to use water at the same rate as in recent years, the city may approach its supply capacity within 15 years.”

In attempting to construct and calculate scenarios of the future, it is important to have a historical perspective: to see the characteristics of past water supply and use in times of water stress; to see the bounds of past extremes in drought and flood and to capture some of the stock dynamics of the components of water systems.

FIGURE 1 ABOUT HERE

However, the historical record is discontinuous and sometimes fraught with inconsistent information. The Australian Bureau of Statistics (ABS) Water Accounts are published occasionally (ABS, 2000; BS, 2004; ABS, 2006) but they give only a static report of water use and not much detail on the different ways water is sourced. Here we are particularly concerned with the major catchments or ‘surface water management areas’ (SWMA) of the State of Victoria (refer Figure 1). To get a detailed historical picture at this level, it is the experience of the authors that you must derive it from numerous disparate data sources. For example, by extracting information from Victorian State of the Environment reports such as Department of Water Resources (DWR, 1989), the Victorian Water Review (2004) or the Victorian State Water Report (DSE, 2005).

The Water Account System (WAS) that we have constructed (Turner et al., 2008) draws on these data but it is also part of, and informed by, an integrated framework of other accounts and modules in The Victorian and Australian ‘Stocks and Flows Frameworks’ (SFF). Each module is an account of some sector of the physical economy of Victoria eg. residential land use or energy supply.

In producing the WAS and other SFFs that are its companions, a great deal of effort has gone into the construction of a complete and consistent historical database. This paper describes the method by which that has been achieved.

The emphasis on completeness stems from the integrated nature of our approach. Water is an important part of many sectors of the physical economy. These sectors, in turn depend on others and it is difficult to reconstruct any coherent history (or produce scenarios of water supply and use) unless you begin with the intention of being complete.

Nor is it sufficient to develop accounting models that simply include or represent the many sectors that involve water. Where relevant, the calculations of these accounts should be connected and self-consistent. Interconnection and consistency is important from a basic accounting perspective: totals and other macro-state variables should be consistent with the sums and combinations of outputs from connected sectoral modules. The nature of the connections is also important for representing the basic mechanics of the (water) system as much as the flow of information.

OUTLINE OF THE WATER ACCOUNTING SYSTEM

This section summarises the calculations in the WAS framework; a detailed description is available in Turner (2008) and the essential mathematics of the WAS is presented in Table 1. It is useful to refer to the diagram of information flow through the WAS shown in Figure 2.

FIGURE 2 ABOUT HERE

TABLE 1 ABOUT HERE

The gross demand for water is established in the ‘Water Required’ module from exogenous information and calculations about population and the economy in other SFFs. There are four modules that use this gross demand information.

The ‘Potable Water Treatment’ module specifies how much of the gross water demand will need to be potable and what infrastructure will be needed to provide that. The ‘Water Re-use’ module determines how much will be re-used and decentralised or on-site re-use of water reduces the actual demand for water to be supplied from the centralised sources, or to be self-extracted from water bodies. The ‘Allocated Water Discharge’ module calculates how much of gross demand will be consumed and amount discharged. The ‘Water Takes Disposition’ module determines from where water will be sourced: river, dam or ground, and how: through a centralised utility or by self-extraction. Rainwater tanks reduce both stormwater flows and the net demand for water from dams, rivers and ground. This reduction and also what flows of water will be supplied from desalination are calculated in the ‘Water Takes Disposition’ module.

In parallel with the above, the calculation of gross water supply, in each SWMA, begins with the rainfall volume and its partition into surface, ground and evapo-transpired (ET) water in the ‘Water Available’ module. The calculations here involve exogenous meteorological and geographical data to ascertain rainfall and ET rates for land use at particular locations. Data about the area of built land is also needed to calculate stormwater flows and to anticipate the fraction of rainwater captured in rainwater tanks.

The water flows in the ‘Desalination’, ‘Potable Water Treatment’ and the ‘Centralised Discharge Water Treatment’ modules all drive the requirements for infrastructure and energy for these types of water treatment. Those energy needs and that for water re-use are accounted for in the ‘Water System Energy Use’ module.

While the ‘Water Takes Disposition’ determines where water supply will come from, the ‘Water Puts Disposition’ determines where all forms of discharged water and stormwater will go to (river, dam or ground). Also contributing to this calculation is the exogenously defined ‘Water Transfer Direct’ module which determines what flow occurs internally between SWMAs and what flows occur externally between SWMA and areas outside Victoria.

It is important to note that the partitions of the total flows to and from the water supply system are made with exogenous shares specifying allocations so that there is no double counting.

Following the puts and takes calculations, the balance of flows to and from ground water, rivers and dams are established in their respective account modules. At this stage of development of the WAS, only flows of ground water, and not stocks, are treated in the Ground Water Flow module since the complex dynamics are not sufficiently well understood to calculate ground water stock levels.

The River Flow Account module is a partial balance since the interaction between river flow and storage must be calculated in the Dam Account module. The latter also incorporates the river and dam network in terms of the hierarchy of river basins and tributaries.

In our work we have used the *whatIf?*® software platform to construct these stocks and flows frameworks which are constructed using the Design Approach (Gault et al., 1987). For more information on stocks and flows frameworks see Foran and Poldy (2002).

METHODS

In the stocks and flows approach, two frameworks of sectoral modules are used, namely the simulation and calibration frameworks. A calibration framework integrates a wide variety of information to initialise the smaller number of variables in the simulator framework. The simulation framework (summarised above for the WAS) then uses parameters and age profiles of stocks to explore possible future scenarios. The simulation framework is also applied to the historical time period, which provides a quantitative historical context for simulated scenarios of the future.

The result is a simulated history that is complete and consistent i.e. complete in the sense that all variables have actual historical data where it is available or else estimated historical data, and consistent in the sense that observed historical data is reproduced and all of the relationships in the simulation framework are observed simultaneously.

The concept of calibration used in this stocks and flows approach is slightly different from that usually understood in computer modelling. More often a complete historical record already exists for some variable and a model's parameter values are modified at calibration so that the outputs of the model match the observed data. In the case described here, calibration is as much concerned (perhaps more so) with the generation of an historical record in the first place.

The calibration process used to achieve the principles of completeness and consistency involves several steps to overcome the problems of disparate and fragmented historical data. This section describes these conceptual steps in something of a hierarchy, while the following section provides more detail in the context of specific historical data related to the WAS. The calibration steps in approximate order are below.

Collating (and Cleaning) Data

All raw data are read into the calibration framework and reviewed separately. The calibration framework identifies the location of the source data, and imports the data as a text file. These files also contain a description of where the source data was obtained. The source data is imported using the disaggregation or categories of the original data. Data that are related to similar model concepts, such as volume of water used, are collated in separate modules of the calibration.

The simplest level of inspection is to detect gross errors in the raw data using graphs and tables, such as negative entries in water volumes. Where such errors exist the original source data are not edited rather a correction is coded within the calibration framework leaving a clearly documented "audit trail".

Comparing Similar Data

Those circumstances where multiple data sets have been collated on similar concepts provide the opportunity to compare the data to identify duplication, conflicts or complementarities. We may do this using the original disaggregation of the data, which allows us to identify any semantic or qualitative differences between similar fields used in the raw data, for example, between "urban water use" from one data set and "domestic water use" from another. Any commonalities or differences help inform us how we might subsequently categorise the raw data.

It is also useful to aggregate over the detail and compare the result with state or national totals. Such comparisons may highlight, for example, missing data in parts of the disaggregation which would otherwise not be obvious. In cases where there is only a single data set, both this step and that of consolidation are skipped.

Categorising

Having established a better idea of the data veracity and overlap, if any, it is now appropriate to begin creating disaggregation or categorises of the data that are more general or common among the data sets. We categorise the fields of different data into a common set of descriptors which are referred to in the *whatIf?*® software as "informant" sets. This point in the calibration process is often an intermediate stage to aid the next step of identifying discontinuities or any conflicts between data defined by a common category. Typically, we aggregate more detail into smaller categories. Later, we may disaggregate (to the informant set of the simulator) when other information is available to help inform how the data should be divided. Ultimately we form categories that match the informants of the simulator variables.

Consolidation

When we are able to compare overlapping and contiguous datasets, such as water use data (see Water Requirements and Re-use), we can then choose the best combination to describe history. (This step is irrelevant where only a single data set exists.) Where datasets conflict, it may be necessary to use information from many sources or judgement to gauge the best way to assimilate information from either set. For instance, data from surveys may be considered less complete than census-based data or that associated with regulatory processes.

Resolving conflicts or harmonising data may involve excluding information, averaging or finding the maximum or minimum values along a time series. As a general rule, harmonising is usually applied to more aggregated data (such as national and state totals) because there is less overlap of data at the disaggregated level. In particular, national and state totals are more likely to be available over longer periods.

Completeness

Up to this point in the calibration, the process has involved working with observed data only. Subsequent calibration actions establish data in all remaining data gaps of the exogenous variables. At the most simple level, described in this section, completeness involves filling the data of a single variable without reference to other data or relationships in the simulator. The more complex situation (described below in the Consistency section) involves imputing data for variables employing constraints or information embodied in the simulator. In this sense, establishing completeness is an integral part of the Consistency step, in the sense that all exogenous parameters of the simulation framework are filled with data.

The simplest application of completeness in the calibration involves filling in the data gaps of a single variable. For example, data do not typically cover the entire historical period of the calibration, such as levels of major storage (see Dam Volume Account section). When there is an absence of good data or other information, interpolation or extrapolation may be required. If no additional data or information is available then trends in the existing data may be used. Alternatively, other time-series data from more closely related variables may be used to infer the extrapolation.

Consistency

This final and complex stage of calibration makes use of data throughout the framework, and the relationships embodied in the simulator framework. A simple example of this involves the disaggregation of a total into the more detailed informant or category. For example, in deriving values for water required by industry in Victorian catchments, we used (1) a state total industrial water use, (2) a normalised share (sums to 100%) of industrial land use in each local government area and (3) a mapping (i.e. conversion table) of local government areas to catchment area boundaries. The spatial aspect of this example is described in more detail later in the section on the Energy Needs of the Water Sector.

More complex applications of consistency take place to impute parameters whose values are largely unknown. Several examples are described below in more detail, such as establishing the fraction of river flow that is abstracted to water storage, adjusting the energy intensity of various water treatment and transfer parameters, and estimating the parameter that shares rainfall between groundwater, surface water or atmospheric flows as final destinations of natural processes.

In these processes, it is sometimes necessary or efficient to use an iterative procedure where the parameter values are adjusted by an appropriate factor based on the deviation of calculated output variables (eg. storage levels) from observed (or target) data for that output. In other cases, a mathematical relationship can be inverted and the parameter directly estimated.

A common example of iterative consistency procedures in SFFs occurs when establishing the age profile of a stock. Typically such data is not recorded. However, if total stock at each time step through history is known and deletions are known (or assumed), then it is a simple but repetitive accounting process to establish the age profile by assigning each positive change in stock level (less deletions) to that “vintage” or time step. Ideally, the time-series of this process would extend over about three times the characteristic lifetime of the stock.

Summary

Depending on the data in question, not all the above steps are necessarily used, or used strictly in this sequence, but collectively they constitute calibration in their application to SFFs. This process begins with an initial inspection of individual source data, and finishes with the population of all variables across the simulation framework.

When all of the exogenous parameters of the simulation framework are filled with data (completeness), this framework should calculate all outputs to match historical data where it is available (consistency). The calibration can be characterised as a mixed top-down, bottom-up process; the top-down nature derives from the system-wide coverage of the frameworks and the use and reproduction of reported aggregates, while the bottom-up nature is associated with the use of detailed parameters and the integration of technical data. At the conclusion of calibration we have a complete representation of the physical history of the system (here that is the Victorian water sector) that is consistent across all the sectors involved. A concomitant result is that we also will have developed values for a subset of variables (often these are intensive variables or the age structure of stocks) whose historical trajectories provide a sensible place from which to launch scenarios of the future.

The following sections highlight several general and important aspects of the calibration steps, especially those associated with completeness and consistency of historical data.

CALIBRATION OF THE WATER ACCOUNT SYSTEM

There were several key variables to calibrate: major dam levels, water use, river basin runoff, water system energy use, inter-basin water transfers, and rainfall. The data used and the degree of calibration required is shown in Table 2. In some cases, such as rainfall data, there was a simple correspondence between the raw data and the inputs to the WAS, or it may involve imputing unknown historical values such that the observed historical data (eg. dam levels) are reproduced by the simulation.

TABLE 2 ABOUT HERE

Spatial Calibration

Often reporting about land use activity, and associated water use, does not use the same boundaries as reporting for water supply (i.e. catchments/SWMA). Mining, industrial and other developed land use information was available by local government area (LGA) boundaries. Agricultural water use data was available by ‘statistical division’ (SD) boundaries used by the ABS.

To transform information from one set of boundaries to another we initially used the spatial split of LGAs or SDs as they map to SWMAs (refer Figure 1). This mapping is represented as a matrix assigning water requirements associated with an activity eg. in each LGA, purely on the basis of the split of their land area across SWMAs.

However, this matrix is only used as a seed for a more sophisticated algorithm that takes into account the total reported water required for a given activity. The algorithm iterates through incremental changes in the matrix elements with the aim of having the sum of all rows and the sum of all columns both equalling that reported total.

This matrix is then normalized with respect to the calculated total for a given SWMA to obtain a matrix of shares (<1) that allocate water requirements for an activity to SWMA boundaries.

Other information such as satellite imagery might be used in the future to better locate water use activity possibly as in Lenzen and Murray (2003).

Links with Other Stocks and Flows Frameworks

Water use information was sourced from a combination of historical data sets and the output of the calibration of the Victorian and Australian SFFs. Water use associated with mining, industrial and developed land use activity by LGA boundaries came from the historical calibration of land use in the Victorian SFF. Water use in the agricultural sector for crops and animals by SD boundaries came from the Australian SFF.

Sharing data achieves consistency across frameworks and provides a further crosscheck to the historical calibration of land use in the SFFs.

Water Requirements and Re-use

The ‘Water Requirements’ module brings together all the variables concerning the water needs of the different sectors of the Victorian economy. These are essentially grouped into industrial, mining, building operations and agricultural water requirements.

Industrial and Mining

Industrial water requirements include those for the production of food, manufactured goods, materials (eg. plastics, metals, chemicals etc.), recycling and electricity. The assumptions behind the water intensities of these processes derive from modules concerned with materials and energy conversions in the Victorian SFF. Water used in energy generation derives from the Victorian SFF, all other are sourced from information in the Australian SFF.

The aggregate water use by 19 different mineral extraction processes in Victoria was taken from the Australian SFF and distributed according to the ‘land use state’ information which specifies in which Victorian LGAs mining activities are located.

Residential

The reconstruction of historical residential water use considered data from the ABS (2000; 2004; 2006), the Bureau of Rural Sciences (BRS, 1985) and the Victorian Department of Water Resources (DWR, 1989) and census data on population and dwellings from 1966 to 2001.

The process by which these data were combined into a single time series demonstrates the categorisation of: ABS “household water use” data; BRS “total domestic”; and DWR’s information about “metered residential” for Melbourne 1972-1984, into a single “residential” category used in the WAS (refer Figure 3). This mostly involved a one-to-one mapping.

FIGURE 3 ABOUT HERE

The BRS datum for 1985 appeared suspiciously low (refer Figure 3) and, while there was a drought in effect at that time, it was also at odds with other information on Melbourne’s historical residential water use in Victorian Government documents (DSE, 2004a). In this case, the consolidation of the data proceeded through the exclusion of this apparent outlier.

The data we had from DWR (1989) referred only to Melbourne. From this we needed to obtain an estimate of Victorian residential water use by first assuming that it is associated with residential dwellings. In another module in the Victorian SFF concerning demography, ABS census information on population and housing had already been calibrated for 1966 - 2001. This was used to derive a ratio of Victorian dwellings to those in Melbourne over history.

The residential water consumption data for Melbourne was adjusted upwards by this ratio to get estimated values for all of Victoria. Estimates for the intervening (unknown) years between 1984 and 1993 were deduced through linear interpolation. For years preceding 1972, a linear trend was extrapolated based on water use in the years immediately following 1972. The final historical time series of residential water use in Victoria can be seen as the black line in Figure 3.

Note that there is no attempt to represent the variability of water use between 1984 and 1993. This might have been calculated through some sort of sampling of variation in the data outside that interval. However, any variability superimposed on the linear trend would have to model both meteorological variation and the subsequent response of households. This is not a trivial task and it is our opinion that calculating variability in residential water use for all years would add little for the amount of extra modelling that would be required.

This compromise in precision has implications about what the final time series can be used for. Our objective of producing long-term scenarios for strategic decision support means that we are willing to forgo yearly variations considering a higher priority on capturing changes over decades.

TABLE 3 ABOUT HERE

Several data sources were considered in deriving the indoor and outdoor water use intensities. Troy et al. (2005) surveyed 29,000 households across Sydney to produce figures for total water use by residential dwellings of different density (see Table 3). Grant et al. (2006) produced similar results for the suburb of Kalkallo north of Melbourne but did not distinguish different density types. The residential water use data from Sydney is consistent with the quantities in the Kalkallo study and it is richer in detail hence it is the basis for the values assumed in the Victorian SFF.

According the ABS Water Accounts Australia 2001 the split of indoor/outdoor use in Victorian households was approximately 65/35 respectively. This is assumed to apply across all Victorian residential land - refer Table 3.

Historical information on water use in buildings was derived from a report by Victoria’s Office of the Commissioner for the Environment (1988). The total water use by buildings at the beginning of all scenarios is consistent with quantities reported in the Victorian Water Review (VWIA, 2004).

Agriculture

The water use in the agriculture sector was obtained from a variety of data sources on both area of irrigated crops and pastures and volume of water use. Despite the large volumes involved, data on irrigation and other water use in agriculture is poor and patchy. The overall approach involved the use and calibration of the agriculture module of the Australian SFF to obtain irrigation water volume from irrigation intensities and area of irrigated activity for SD in Victoria, as well as ABS data available for a small number of years. Further data from the ABS and DWR was used to convert volumes of water used in SD to water regions.

The beginning of this agriculture water use calibration is the calculation of irrigation intensities (volume per unit area). Initial estimates were made from water use volumes given by the ABS (2000; 2004; 2006) and other miscellaneous sources, divided by the area of irrigated crops (including fruit and vegetable horticulture) and sown pasture. These areas were obtained from a variety of data sources used in the extensive calibration of the Australian SFF agriculture module (Dunlop and Turner, 2003), including data from the Inter-Regional Database (IRDB), ABS and national State of Environment reports (ABS, 2001a; ABS, 2001b; ASEC, 2002; Zhang et al., 1999). The initial estimates of irrigation intensities at SD were scaled by comparing aggregated irrigation volumes with state level data from the National Land and Water Resources Audit and Australian Water Resources Council (AWRC, 1987; NLWRA, 2001). Revised irrigation volumes were calculated (from intensities and areas), and combined with ABS Victorian data by using the higher data for those years. Due to the lack of data on water used directly for livestock, this volume was calculated using the ratio of livestock to crop/pasture water volumes from ABS (2006), and the irrigation volume multiplied by this ratio.

The final calibration step was to convert the SD based data to that for Victorian water regions. Both DWR and ABS data for 1985 provide comparable breakdown by SWMA, and an average of these data sources was used to calculate the share apportioned to each water region. This share was applied to the state total of agricultural water use obtained from an aggregation of the detailed SD time series data described above

Re-use

On-site re-use generally set to zero in history except for heavy industry processing and assembly and recycling industries who are assumed to re-use 30% of their water requirements on site. Mining is assumed to re-use 80% of their water. Note that this is not the same as centralised recycling which is represented in the Waste Treatment and Collection section.

Natural Water Supply

Calculating natural water supply involved distributing total rainfall in a catchment to evapo-transpiration (ET), runoff to surface waters, and groundwater in such a way that the calculated runoff matched the reported mean annual runoff (MAR).

Rainfall data was selected from rainwater gauges representing points in the upper reaches of each Victorian SWMA using the *Rainman Streamflow 4.3*+ software package and database (Clewett et al., 2003). It is possible to use other hydrological models as alternative sources of data but we have focused on observations in the first instance to create an empirically based accounting system free of model assumptions.

The Department of Water Resources (DWR, 1989) has values of historical MAR up to 1989 for each SWMA and further information is available in the State Water Reports (DSE, 2005; DSE, 2006).

For each SWMA, flow to groundwater was assumed to be the state-wide average of 1% of the total rainwater input reported in (DWR, 1989). The calibration of runoff takes into account the different land-use in each water region, allowing ET and runoff rates to differ by water region and land-use, and over time. Zhang's (2003) evaporation rates for different land cover (trees and grass) were used in conjunction with land use information by LGA from the Victorian SFF.

The water balance of 'natural' flows for the whole of Victoria can be summarised as in *Water Victoria: A Handbook of Water Resources* (DWR, 1989):

$$\mathbf{Rainfall}\ (\mathbf{100}\%) = \mathbf{ET}\ (\mathbf{84}\%) + \mathbf{Runoff}\ (\mathbf{15}\%) + \mathbf{Flow\ toGroundwater}\ (\mathbf{1}\%) \quad (1)$$

We have elaborated on this, disaggregating each variable in the above equation by location, by land uses at that location, and by separately identifying that part of runoff that comes off the hard surfaces of developed land as storm water.

Storm water simulations are driven by rainfall and the proportion of developed land (housing, commercial, industrial etc.) in a given catchment. The latter is directly linked to a development history or scenario represented by the ‘land use state’ variable which again comes from Victorian SFF. Since there are very few historical records of storm water flows this is truly simulated and not calibrated to agree with any data.

Our calculations also make allowance for the subtraction of rain collected for rainwater tanks from the rainfall total. The calculation of the rainfall intercepted by roof systems considers both the roof area of developed land (the potential capture area) and the fraction of that area actually engaged in collecting rainwater.

The water balance calculations retained the assumption of a 1% distribution to groundwater and it is by holding this factor constant that we used rainfall and runoff data as independent variables to impute the complete ET data set for each catchment. These calculations effectively embed the information about land use and geography in the values of ET for each catchment area. The order of magnitude of ET may be compared with the values for combined ‘in stream losses to groundwater infiltration and ET’ reported in the State Water Reports (DSE, 2005; DSE, 2006).

While some historical time series data for specific SWMA were available, information on surface flows or ET was not always so forthcoming. Given MAR values for 1989 (DWR, 1989) and 2000 (NLWRA, 2000) we can at least deduce the fraction of rainfall going to surface flows for those years. For time points outside those years we assume the same fraction of rainfall goes to surface flows and for the intervening years we presume a linear transition in the fraction to surface flow.

Water Management

In the WAS water is considered to be sourced either through a centralised system or by self-extraction from dams, rivers and ground water. In addition there is the potential direct capture of rainwater by rainwater tanks and the capture of stormwater.

The source of water varies with location: in south-west Victoria, for example, there's a greater proportion sourced from ground than in the East Gippsland area where most water is extracted from the surface. The proportion of water sourced from surface, ground water and the volume and distance of inter-regional transfers for each river basin was based on figures published by the Victorian Department of Water Resources (DWR, 1989).

The Victorian data in Water Accounts Australia 2001 (ABS, 2004) suggest that approximately 10% of piped water is lost in transfer and losses in canals are assumed to be a minimum of four times this. We do recognise that these rates can vary depending on the location and mode of water transportation. From consultations at DSE we know that there exist open canal irrigation systems with combined evaporation and leakage losses of up to 90%.

In addition to inter-regional transfers along pipes and canals, particular regions source their water from up-stream catchments (eg. along the Murray River). River networks such as this are sensitive to upstream diversions and we have been careful to capture how such extractions affect the flow of water to downstream catchments.

Potable Water Treatment and Supply

It was assumed that all land uses that involved built structures required 100% potable water. The fraction of water required that was actually consumed by different sectors was assumed to be: 20% for the residential, health, education, commercial, retail and business sectors; 10% in processing and assembly; 30% for all electricity generation involving steam generation or water cooling; and 90% in agriculture where production is reliant on high levels of evapo-transpiration. These are necessarily crude assumptions based on input from experts in the fields or unpublished information and they highlight the need for more data collection on this topic. In the advent of more or better information, the calibration framework can easily be updated.

Waste Water Treatment and Collection

The proportion of waste water going to centralised waste water treatment was taken from ABS Water Accounts 1994-1997 and 2001: 95% from all residential and built land, 10% from processing and assembly and recycling industries.

All waste water is assumed to be of black water quality. Though it is acknowledged that some part of waste water flows will be grey water, this is generally mixed with black water in Victorian waste water treatment. All waste water treatment is assumed to be to tertiary standard. The calibrated energy intensity of discharged water treatment is dominated by the data from Melbourne (Kenway et al., 2007). Melbourne's discharged water treatment energy requirements are higher than most Australian cities because the sewerage has to be pumped further. For 2004-05 a system average of 0.39 KWhr/m^3 for treatment alone but including pumping of discharged water, this becomes 0.94 KWhr/m^3 (Kenway et al., 2007). Again, the low resolution of these macro statistics indicates the need for further research. In the absence of more detailed data we are at least reassured that our calibration process will result in agreement with reported aggregate quantities. All direct discharge and stormwater is assumed to go into rivers.

Water Transfers

The first guide for information on water transport between SWMA was *Water Victoria: A Handbook of Water Resources* (DWR, 1989, p63). Table 4 shows what proportion of water received by a SWMA comes from which donating SWMA.

TABLE 4 ABOUT HERE

Generally all imports are to dams for water from both canals and pipes except for the Upper Murray and Loddon SWMAs which receive water to river from canals. Loddon and Avoca SWMAs also receive water directly to their respective rivers via piped input. About 324 200 ML/year is imported to the Mallee-Wimmera catchment by canal and 142 000ML/year is imported into Kiewa and Ovens basins by pipe from outside the state (DSE, 2005; MDBC, 2003).

River Flow, Groundwater and Dam Volume Accounts

These are the accounts at the end point of the WAS that have to tally with historically observed quantities. Given that they are the culmination of many of the calculations in the WAS, their output is heavily reliant on the calibration of numerous preceding variables. In the river flow and groundwater accounts, the final result is little more than a basic accounting exercise but the involvement of water management in the form of diversions to dams and the complication of river networks, means the dam volume account requires a more sophisticated calibration.

River Flow Account

This module requires no calibration at all since it contains purely an account of the various inflows and outflows to rivers excluding flows from tributaries and transactions with dams. The River Flow Account depends on the outputs of preceding modules but in one sense it is incomplete as the ultimate calculation of river flow occurs in the Dam Volume Account after contributions and extractions to and from dams and the consequences of river networks has been calculated.

With the constraints outlined above, the biggest determinant of river flow at this stage in the WAS is rainfall in the catchment. Depending on the SWMA, water is generally extracted from dams or ground water, for all water uses, though in most SWMA some smaller amount is extracted from rivers.

Ground Water

Ground water is accounted for simply by subtracting extractions from natural inputs for a given region. No assumptions are made about the subterranean transfer of water between regions. The hydrology of ground water systems across Victoria is outside the scope of the WAS though the simple metric of net flow to ground water is an indicator of sustainable extraction rates.

Dam Volume Account

The calibration task here is to reproduce observed dam levels by estimating suitable parameters. In the WAS, all major dams within a region are treated as a lumped storage. The calibration of total dam volumes for a given SWMA involved several interdependent components: multiple dams and inter-catchment transfers, flows from rivers, dam evaporation, and other factors. A key parameter in the calibration is, f, the fraction of river flow in a region that is not diverted to storage. Within a single (isolated) region, this fraction by-passing storage can be estimated from the balance equation for storage (where ΔD, the change in storage level from one time step to another, is the difference between inputs and outputs):

$$\Delta D = (1 - f) \times F + I - R - E \qquad (2)$$

where F is the river flow potentially entering the storage, I represents other net inputs such as transfers from other regions (if made directly to the dam), R is the release of water from the dam, and E is loss due to evaporation. Equation (2) is readily solved for f.

Since the WAS incorporates a river network, it is necessary to use an iterative procedure because the input to a lower dam depends on the river flow exiting the upper regions after solving the storage balance in those regions. For the lower region, the river flow above the dam ($F^{'}$ to be used in Equation (2)) is the sum of, F_i, net river flow internal to the region (i.e. due only to river inputs and outputs that occur within the region, which is calculated elsewhere in the framework) and, F_u, the river flow exiting the upper region: $F^{'} = F_i + F_u$. F_u is calculated in the previous iteration from fF. The number of iterations required is just the number of basin levels in the hierarchy of the river network.

Despite the apparent importance of water storage, data for many of the factors in Equation (2) was not readily available for this calibration exercise. A discontinuous record for observed dam volumes of the major dams in Victoria was collected from a range of sources (GMW, 2005; MDBC, 2005; MW, 2005). A linear interpolation was performed over the years where no data was available to get a best estimate of observed dam levels. Net inputs to river flow (excluding storage abstraction) were calculated from the WAS model, using the calibration steps described in other sections above. Other inputs to storage were based on limited data on inter-catchment transfers (refer Table 4). Evaporation loss was calculated from published figures of major dam areas and estimates of evaporation rates. No data was obtained on dam operations, such as the river flow abstracted to storage or the release of stored water.

In the absence of further research to obtain such data, the appropriate calibration approach was to impute f to reproduce storage levels across Victoria using the other data. Since release of water from dams within each one-year time-step could not be discerned (in an accounting sense) from the river flow by-passing the storage, R was initially taken to be zero. However, in order for the observed data on major storage levels to be reproduced it was also necessary to adjust evaporation rates for several dams and impute infrequent but large release of water from one major dam. The releases occur in 1994, 1995 and 1998 following years of low rainfall, and are equivalent to a large fraction of the river flow in the upper catchment of the Murray River.

The flow of the Murray River at its exit point from Victoria (the South Australia border) is an important metric by which to gauge the success of the overall calibration of the WAS. Many of the rivers of SWMA flow into the Murray River and there are a number of major dams located on it. Apart from being a major water way, the Murray River flow represents the end result of much of the calibration procedure and carries the cumulative uncertainties about flows from many catchments.

FIGURE 4 ABOUT HERE

Despite this, the WAS calculated flow in the Murray compares favourably with data from the Murray-Darling Basin Commission (MDBC). In Figure 4 the long term median and average flows in the Murray are shown with the same measures as modelled for pre-settlement conditions. The WAS calculated flow in the Murray for earlier historical years is closer to the natural conditions, due to lower water use in the river system. The flow calculated for the later historical years are in agreement with the average and median values for current conditions. The good comparison provides a degree of validation of the WAS and its calibration, particularly as the Murray River flow at the SA border is the compound result of many influences.

In the Murray-Darling River system Kirby et al. (2008) found that “about 75% of inflows, outflows, gains and losses is gauged, and about half of the remaining water balance can be attributed with additional data and modelling. However, large unattributed losses and noise remain, amounting to about 12% of the water balance on average.”

In our WAS this unknown flow is not explicitly recognised though it may be implicitly absorbed in several variables, for example, ET rates or f from the equations above. If, for example, the calculated flow was too high and river flow data were available and lower than our calculations, then we would have to make a judgement about what variables to adjust to calibrate to the lower river flow.

Energy Needs of the Water Sector

Deducing the energy consumption by the water sector presents an excellent demonstration of every stage in the calibration process using a wider collection of data inputs (refer Figure 5). In particular, the ‘consistency’ stage of calibration of the water sector’s energy needs provided constraints on the connected Water Transfers module.

Both extensive and intensive variables were calibrated so that the total calculated electricity use for water treatment and transport matched or exceeded the reported total by ABARE (2007). Note that the majority of energy provided to the Victorian water sector is in the form of electricity. Hence, in variable names we have used the terms “energy” and “electricity” interchangeably. The collection and categorisation of data proceeded as follows.

FIGURE 5 ABOUT HERE

The quantity of potable water treated and delivered was calculated from ‘upstream’ population, industry and land use modules in the Victorian SFF – see Figure 5. Kenway et al. (2007) have collated statistics from the water utilities of four major Australian cities and, from their figures, the electricity needed per litre had a system wide average of 470j/l for treatment and distribution of potable water in Melbourne in 2004-05. Kenway et al. (2007) also calculate an intensity of 3400 j/l for waste water treatment and pumping in Melbourne for 2004-05. Both these intensive figures been taken to be representative for the state as, according to the Victorian Water Industry Association Inc. (VWIA, 2004), the vast majority of Victoria’s waste water discharge occurs in or around Melbourne.

In the process of collecting information on water supply and discharge, volume data on the re-use of water were found in ABS (2000; 2004; 2006) and used to estimate the electricity required for water re-use. This re-use mainly occurs in mining, processing and assembly and heavy industries. Where the energy intensity of the treatment of re-used water was unknown, we estimated this to be half that for potable water treatment. This estimation comes from the simple reasoning that water is treated to be re-used but not to the same degree as potable water. Information on the energy intensity for desalinating water varies depending on technology and the local salinity of water or seawater being desalinized. While the approximate figure of 17Kj/litre was taken from the Melbourne Seawater Desalination Plant Feasibility Study (GHD, 2007), no water had been sourced through desalination over the historical record.

Having obtained reasonable figures for the intensive and extensive variables concerning potable water supply, re-use and wastewater discharge, the remaining calibration task focussed on the electricity required for transfers of water between SWMA eg. for irrigation. The preceding intensive variables could be reasonably assumed to apply across history and geography, but the variation in flows between SWMAs and differences in geography, did not permit such flexibility with what we could assume about the energy intensity of water transfers. This situation was exacerbated by the paucity of time series data on water transfer flows. Transferred water flows were based on DWR (1989) information for 1986 and the estimated distance that water travelled was based on known canal or pipeline lengths.

One aggregate reference, to calibrate to, was ABARE's (2007) historical time series total energy requirement for Victoria's water sector (1974 to present). However, there remained conflicts between that top-down total and a bottom up sum of the components mentioned above (refer Figure 6). What follows is the 3-stage process by which we arrived at the energy intensities and quantities of water transport while attempting to be consistent with the aggregate statistics.

FIGURE 6 ABOUT HERE

Data from Kenway et al. (2007) and known transfers between Thompson and Yarra SWMAs, DWR (1989, p64) were used to get an initial value for the energy intensity of water transfer, 3.3 Gj/Gl/km. This was then used to derive a first estimate of energy for water transport which was added to the energy required in potable, re-used and waste water to produce a calculated total. This was to be compared to the reported total in ABARE's historical time series (T_{ABARE}).

The only comprehensive data we had for transfer flows was from DWR (1989) for 1986. This was used in conjunction with the 1986 ABARE total as summarised in Equation 18. This adjusted the energy intensity of water transfer downwards so that the calculation of aggregate electricity needs for the Victorian water sector matched ABARE at 1986 (refer Figure 7).

$$I_{\mathrm{int}} = \frac{\left(T_{ABARE} - pot - dis - reuse\right)_{1986}}{flow_{1986}} \tag{3}$$

Where I_{int} is the intermediate energy intensity for water transfer, $(T_{ABARE} – pot – dis – reuse)_{1986}$ is the residual after subtracting the potable, waste and reused water energy requirements from the ABARE total for 1986 and $flow_{1986}$ is the water transfer flow datum for 1986 multiplied by the distances over which that water flows.

FIGURE 7 ABOUT HERE

Where the calculated total electricity required ($T_{calculated}$ shown as the pink line in Figure 7**Error! Reference source not found.**) deviates below the ABARE historical data, the water transfer energy intensity and transfer flows were both adjusted proportionally so that the ABARE data is matched - refer to Equations (4) and (5). At any time where $T_{calculated} > T_{ABARE}$:

$$I_{final} = \sqrt{\frac{T_{ABARE} - T_{calculated}}{I_{\mathrm{int}} \times flow_{1986}}} \times I_{\mathrm{int}} \tag{4}$$

$$flow_{final} = \sqrt{\frac{T_{ABARE} - T_{calculated}}{I_{\mathrm{int}} \times flow_{1986}}} \times flow_{1986} \tag{5}$$

In Equation (5), $flow_{final}$ is the final estimate of water transfers multiplied by the distances over which that water flows. Where $T_{calculated} > T_{ABARE}$, those variables remain unchanged from their values at 1986. We assume the same relative uncertainty to $flow_{final}$ and I_{final}. Both variables are equally unreliable, deriving from single measurements where no absolute uncertainties were known.

FIGURE 8 ABOUT HERE

The final total calculated energy requirement (pink line in Figure 8) for water transfers = $I_{final} \times flow_{final}$. This is summed with the energy needed for all other water services and the total matches ABARE's historical data exactly after 1986. This is due, in part, to an increasing energy requirement for water transfers (blue line in Figure 8).

The allowance to exceed ABARE's historical statistics is based on the fact that data was collected from surveys which are, if anything, more likely to produce underestimates than otherwise (Baynes, 2007).

DISCUSSION

We have presented two detailed examples of a method for reproducing the physical history of the Victorian water sector. We used available data from the water-sector in concert with a framework of models that simultaneously re-constructs the history of other sectors of the physical economy of Victoria. The basic method comprises a series of steps: collating and cleaning data; comparing like source data; categorising data into common sets; consolidating like data; completing the data fill in parameters where gaps exist; and consistently imputing the values of parameters where there is no observed data, in keeping with the logic and relationships of the simulation framework, while reproducing other historical data.

This approach adopted in the WAS and other stocks and flows frameworks, relates to the objective of creating a transparent decision-support tool for strategic (long-term) resource management. The system is represented ideally as the complete collection of physical processes, expressed in terms of indisputable accounting identities for example, the storage balance Equation (2), with these incorporating all appropriate inputs for the decision-making process. A firm empirical basis is provided since the calibration predominantly employs and reproduces historical data.

Advantages

One of the merits of this approach is that it's a tractable, consistent and systematic way of 'bringing it all together'. Another way of congregating information might be through relational databases but this would not present a user with the same clarity about the processes of data conflict resolution and consolidation.

A significant, though seemingly obvious, insight from such calibration processes is that considerable information is obtained from early and repeated examination of the historical data as it is integrated in the SFF. This informs assumptions about how historical data actually relates to the variables in the simulation framework. Our experience has shown that poor assumptions are often made about the integration of historical data if the results of the integrated data are not viewed progressively in the calibration process.

The explicit approach of representing processes, even where data is lacking, helps in recognising where further data collection would be useful. Sensitivity analysis or related explorations of the system can identify the key parameters or driving factors, on which data collection can be focused. Further historical or measured data may then be incorporated, and a new history for the system calculated.

Considerations

By being broad in scope we have relinquished some precision. We could be more detailed or disaggregated in our categories or use more detailed time series or time steps less than one year. But this raises the question of how much precision do you need to be accurate?

For example, it might be preferable to have detailed time series of intensities for waste water treatment. This might represent the changing technology and standards applied. In the absence of more information, we have used values from a single time point (2005) which are at least based on current knowledge and represent a reasonable estimate until more historical data comes to hand. Another aspect of being aggregate is that some detail on flows may be subsumed in a more coarse data object or not be represented at all. For example, losses from the distribution of potable water to urban users may not be important at a state level but could be significant for particular urban catchments. Future versions of the WAS may be extended to capture such detail,

While an aim of the calibration process is to make maximum use of existing data and logical relationships, some judgement is often required. For instance, we may have differing confidence in some related data sets, and chose one as an authority in preference to another eg. volumes (of say water used) are likely to be more reliable than reported intensities (eg. outdoor water use per unit garden area). This choice is also in keeping with the overall purpose of providing whole-of-system analysis in our stocks and flows frameworks i.e. volumes or flows of physical quantities and the impact on stocks.

Judgement is also required when the values for several parameters are not well known, but collectively determine an observed output, such as the volume of inter-basin water transfers and the energy intensity of those transfers contributing to the total energy used in water transfer. This occurs because SFF are designed to represent the detail of processes and relevant parameters are included even if relatively little data is available. The calibration process and the *whatIf?f*® software make the data, logic and assumptions employed completely open to inspection. We adopt this transparency and process-oriented approach to help identify, among other things, where further data acquisition and research would be beneficial. Additions to and revisions of the simulated history can be made in the light of new data and knowledge. Further discussion of the issue of dealing with uncertainties is provided below.

Uncertainties and Unknowns

There is a key difference between our calibration approach and those of more detailed hydrological models for example SIMHYD (Chiew et al., 2002; Kirby et al., 2008). A hydrological model is constructed to represent as much detail about the dynamics of the system as feasible and its parameters are initialized with known values, fitted using recursion calculations or simply by estimation. Then the model is run to simulate over a time course and the outputs of the model are compared with available historical data. Parameters may be fine tuned but there is usually some error, ε that represents the limit of the model to exactly reproduce historical data. This error term may derive from the external input to the model or it may be a result of the internal limitations of the model, for example, an overly simple representation of hydrological dynamics or an under parameterization (Cook et al., 2005).

This error term may be appropriate for a critically determined model where there are an equal number of independent variables as equations that involve them. In contrast, in the WAS there are many more independent variables than equations and process relationships are represented even if there is an apparent lack of historical or measured data i.e. it is greatly under-determined. Many of the variables and parameters for instance are highly disaggregated. For example, the *single* parameter determining the immediate destination of rainfall has the dimensions of location (29 SWMA), land use (14 types) and destination (evapo-transpiration, surface or ground) representing a total of 1218 time series. For an under-determined system, one or more variables can have a range of values that are consistent with other variables in the framework and with scientific understanding.

In the set of simplified equations (refer Table 1) representing the collection of calculations in the WAS, there are 15 equations and approximately 25 or more variables that lack data (refer Table 5). The extent that the system is under-determined decreases as more system linkages are incorporated, such as the link employed in this work between the water system, and population, land-use and energy frameworks.

TABLE 5 ABOUT HERE

Importantly, the nature of the system accounting relationships remains relatively simple throughout the framework and this limits the instability that could arise from it being under-determined.

Furthermore, judgements and calibration processes that impute otherwise unknown parameter values are open to inspection via a diagrammatic interface to the coding and all data in the calibration framework. Therefore, debate and improvements are focused on data, not on the “model”.

The simplicity and transparency of the WAS suggest that calculating a residual or error term would require substantial effort and produce little extra useful information about uncertainty.

CONCLUSIONS

The purpose of the WAS, in connection with the Victorian SFF, is to simulate and explore many alternative future scenarios of water sourcing, treatment, delivery and end use cognisant of the historical record.

Our methods employ calculations which enable us to reproduce historical data exactly *where that data exist*. This is possible because of both the linear accounting nature of the mathematics and a comprehensive use of relevant historical data. Where historical data does not exist, we use a transparent process of data modelling that is open to inspection and accessible to review.

This paper presents an efficient way to congregate many, often disparate data sets to build a coherent picture of the physical history of water in Victoria. This information also connects to other SFFs to enable long term, cross-scale simulations based on a topically broad and temporally deep historical calibration. Ultimately this feeds into a simulation framework capable of producing catchment level outputs for strategic decision support such as the operational and embodied consumption of water, flow in river networks and the energy cost of transporting and treating water.

ACKNOWLEDGMENTS

This work inherits much from the data, methods, and results of the Australian Stocks and Flows Framework (ASFF) and we are grateful to the creators of ASFF for their continuing support. In particular we would like to recognise the technical guidance of whatIf? Technologies® who are the originators of the software we used. This paper has benefitted greatly from the informed and detailed comments by Freeman Cook (CSIRO) and Joe Lane (Queensland Water Commission). This research was supported through CSIRO's Water for a Healthy Country Flagship and The State of Victoria Department of Sustainability and Environment.

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Figure 1. Maps showing the surface water management areas (SWMA) and major rivers of the State of Victoria and inset the boundaries of Victorian local government areas (LGA)

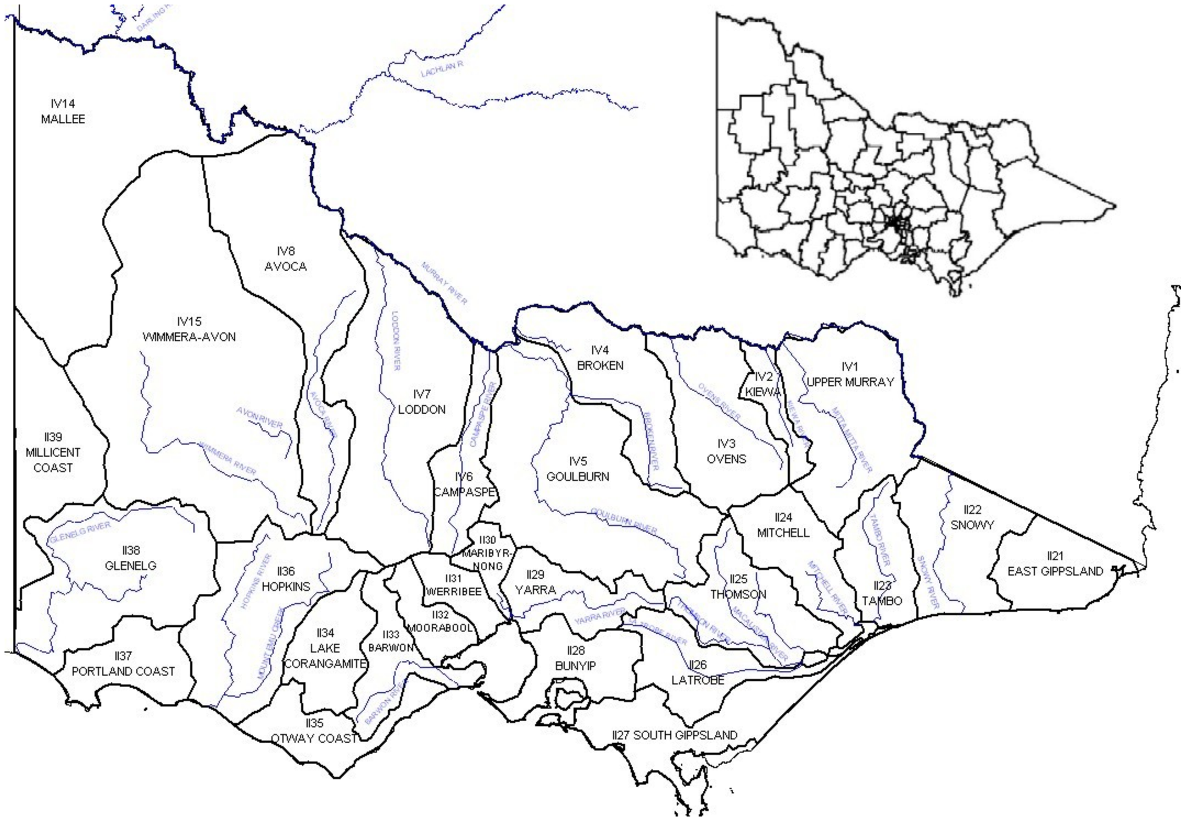

Figure 2. Information flow in the WAS. Solid line indicates information about available water, dashed line shows water required and the dotted line shows the flow of information about energy needs of the water sector. "Water Puts" refers to the destination (ground, river or dam) of water discharged or transferred and storm water. "Water Takes" refers to the sourcing of water from rain collected on rooves, from ground, rivers or dams

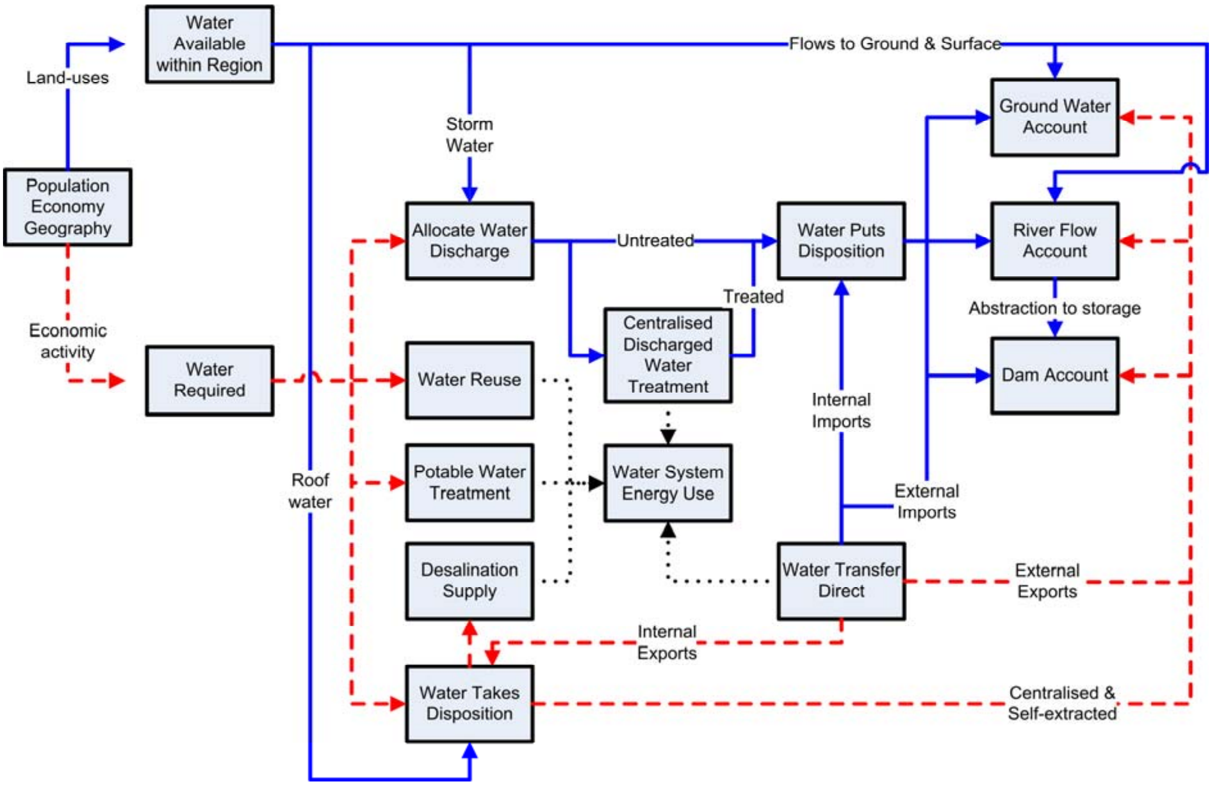

Figure 3. The raw data used and the final historical time series of residential water use in Victoria. DWR refers to the Victorian Department of Water Resources, ABS is the Australian Bureau of Statistics and BRS is the Bureau of Rural Sciences

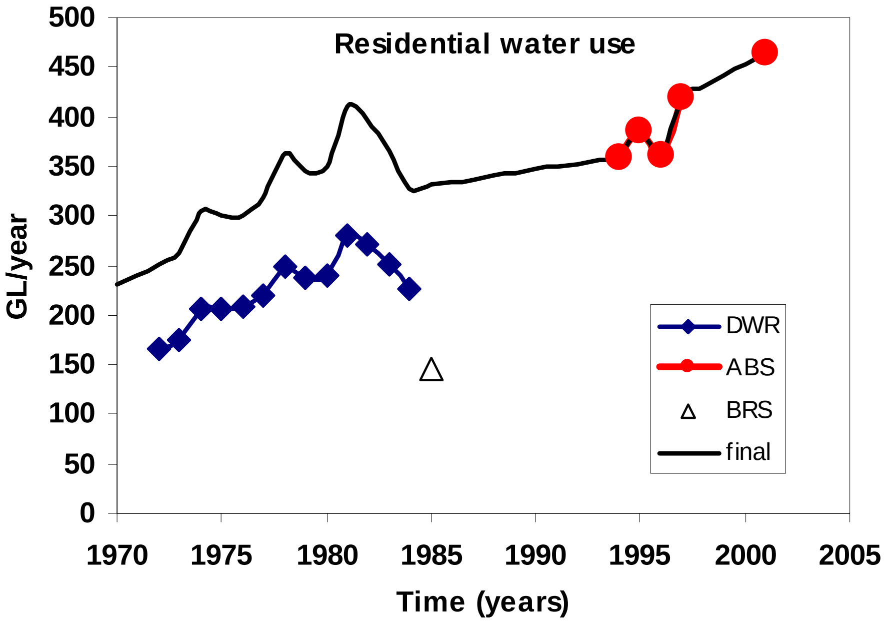

Figure 4. Flow of the Murray River leaving Victoria at the South Australian border. The time series is our calculated historical data. The average and median annual current or natural conditions flows are the median and average of 109 years (1891-2000) of modelled current or natural conditions flow from MDBC (2003)

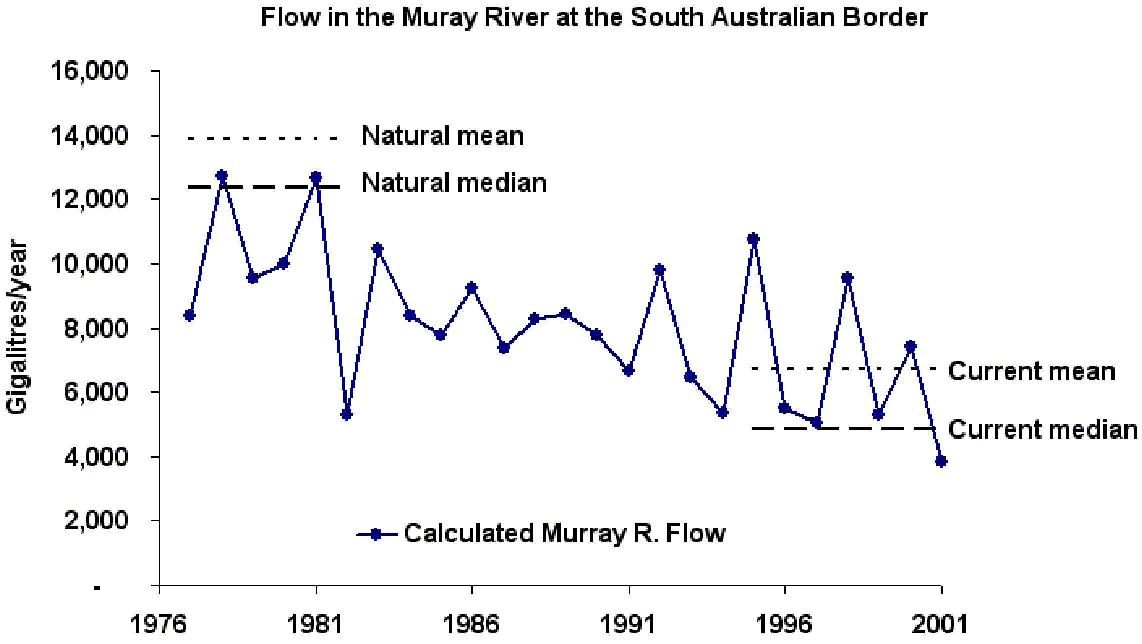

Figure 5. Outputs from the Victorian SFF sectoral models drive water requirements. This subsequently determines activity for different water services. The electricity consumed by these water services is calculated in the "Water System Energy Use" account

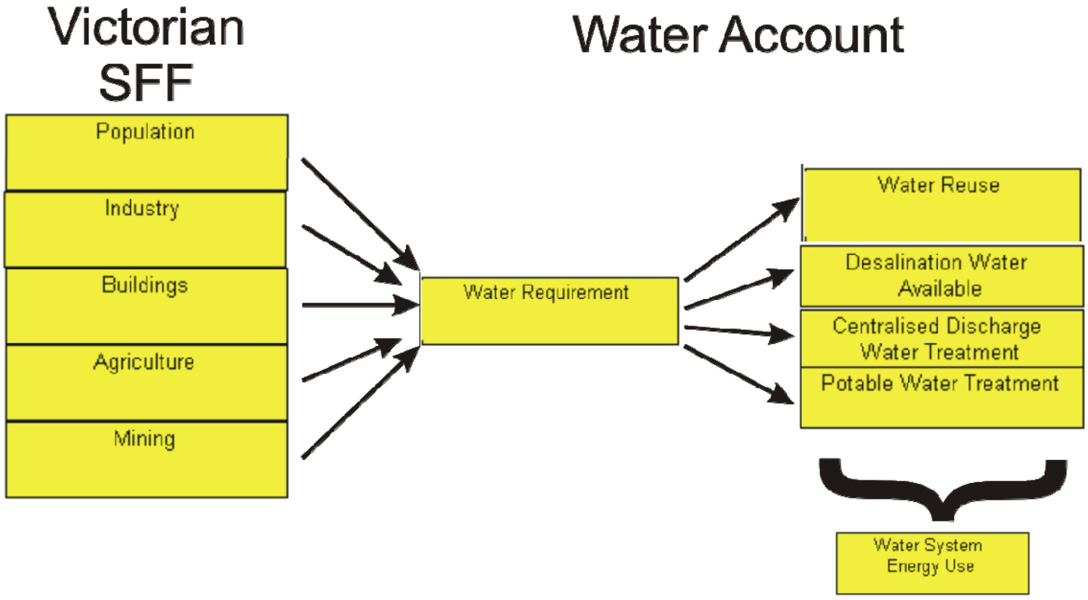

Figure 6. The first estimate of energy intensity for water transfer used to generate the total electricity for water transfer (blue line). This was added to all other water related energy needs to produce the calculated total (pink) to be compared with ABARE's historical data (black)

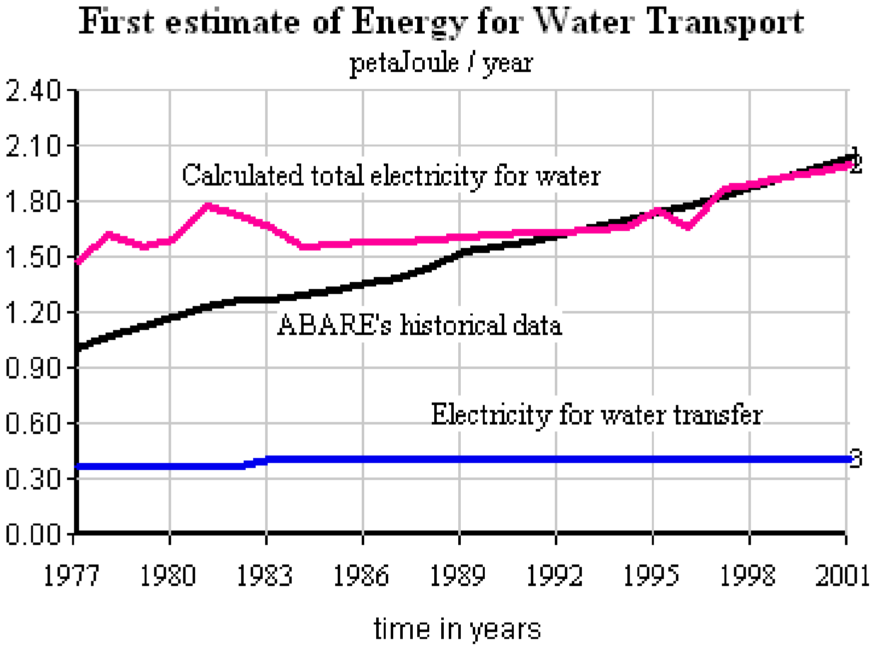

Figure 7. Intermediate estimate of electricity for water transfer (blue line) using data for transfer flows in 1986. The small change at 1983 is due to the Thompson-Yarra pipeline coming online

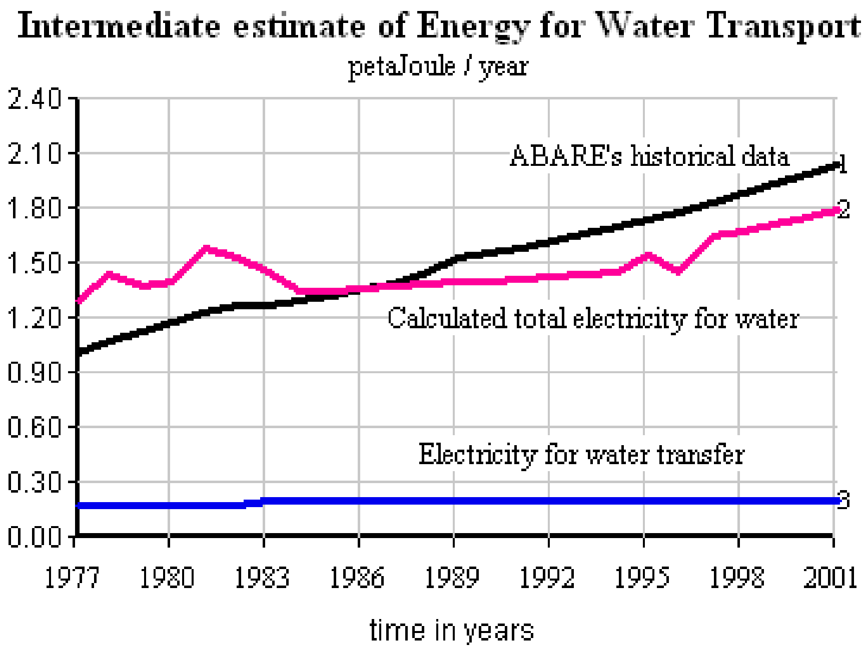

Figure 8. Final step in the calibration of energy required for water transfers

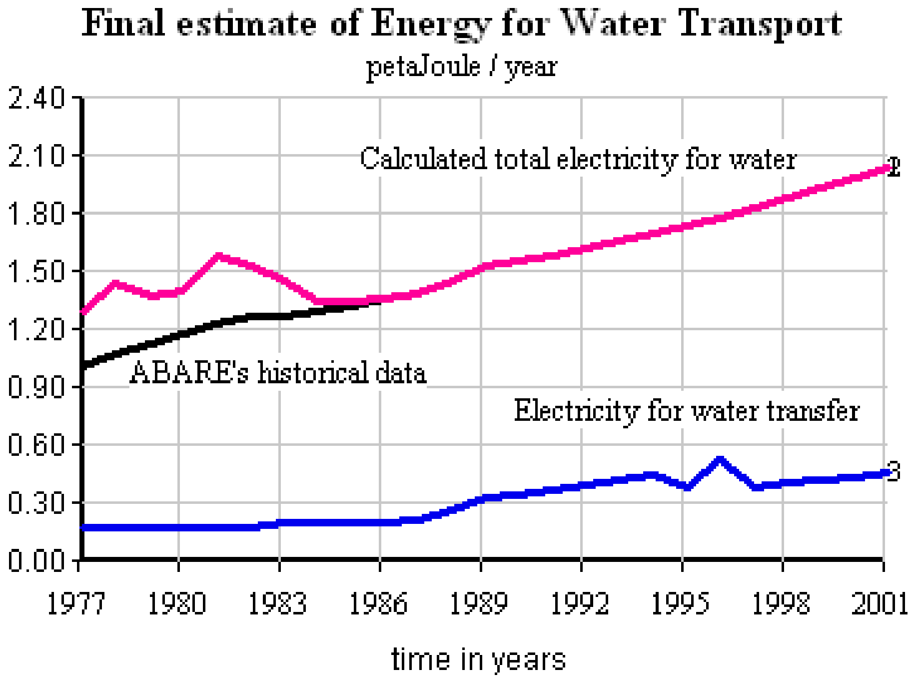

Table 1. The following set of equations summarise the key relationships embodied in the WAS. An explanation of the symbols is given in the lower part of the table

Description	Equation	Number
Natural availability of water	$W^{nat}_{l,d} = s_{l,d} R(A_l - fcA_u)$	1
Water required	$W^{req}_{s} = a_{s,LGA,wr}(W_i + I_{u,LGA} B_{u,LGA}) - r_s$	2
Allocation of water discharge	$W^{trt}_{tr} = W^{req}_{s}(1 - f^{con}_{s}) f^{dis}_{s} s^{trt}_{s,tr} + Sf^{trt}_{u,tr}$	3
	$W^{dis}_{s} = W^{req}_{s}(1 - f^{con}_{s})(1 - f^{dis}_{s}) + S\left(1 - f^{trt}_{u,tr}\right)$	4
Direct water transfers	$W^{exp}_{wr,p} = M\left[\sum_{wrt} W^{imp}_{wrt} s^{tran}_{wrt,wrf,p} / (1 - l_{wrt,wrf,p} d_{wrt,wrf,p})\right]^{wrf}_{wr}$	5
	$W^{imp}_{wr,p} = M\left[\sum_{wrf} W^{imp}_{wrt} s^{tran}_{wrt,wrf,p}\right]^{wrt}_{wr}$ Where M[] represents the mapping of *wrf* → *wr* or *wrt* → *wr*	6
Water puts disposition	$W^{put}_{b,tr,dis,imp\{s,t\}} = W^{tr,dis,imp}_{\{s,t\}} s^{put}_{tr,dis,imp,b}$ where $b = gnd, riv, dam$	7
Water takes disposition	$W^{take}_{b} = s^{take}_{b,s,ext}(W^{req}_{s}(1 - f^{des}_{s}) - W^{roof}_{u} + W^{exp}_{wr,p})$	8
Ground water flow	$W^{gnd} = \sum_{in,z} W^{in}_{z,gnd} - \sum_{out,z} W^{out}_{z,gnd},$	9
River flow account	$W^{riv} = \sum_{in,z} W^{in}_{z,riv} - \sum_{out,z} W^{out}_{z,riv},$	10

Dam account	$W^{dam} = \sum_{in,z} W_{z,dam}^{in} - \sum_{out,z} W_{z,dam}^{out},$	11
	$D = \sum_{time}^{t} \left[(1 - f^{bypass})(W^{riv} + W_{out,up}^{riv}) + W^{dam} - V - R^{dam} \right] + D_{time=0}$	12
	$W_{out}^{riv} = f^{bypass} W^{riv}$	13
Water treatment capacity	$C_{tr} = \sum_{time}^{t} \left(W_{tr}^{req,dis} s_{tr,tl}^{trt} - C_{tr}^{-} \right) + C_{tr,time=0}$	14
Water system energy use	$E = \sum_{tr} \left(C_{tr} e_{tr} \right) + W_{wr,wr,p}^{exp} d_{wrt,wr,p} e_{wr,wr}^{exp}$	15

Variable	Meaning (units given in [])
$W_{l,d}^{nat}$	flow of water originating from rainfall that goes to environmental destinations (*d*), for each land-use type (*l*), [l/a]
$s_{l,d}$	share of rainfall flow to each environmental destination(d), for each land-use type (*l*)
R	annual rainfall for a water region [mm/a]
A_l	land area within each water region, by different land-uses (*l*) [m^2]
A_u	roof area within each water region, by type of built area (*u*) [m^2]
f	fraction of roof area used for rain-water capture in tanks
c	proportion of annual rain-water flow captured by roof tanks
W_s^{req}	net water required by each sector (*s*) [l/a]
W_i	gross water required by non-urban sectors (*i)* [l/a]
r_s	re-use of water locally within a sector (*s*) [l/a]
$B_{u,LGA}$	area of built land-use [m^2]
$I_{u,LGA}$	intensity (volume per unit area) of water use in built areas [l/m^2]
$a_{s,LGA,wr}$	(mapping) parameter for converting data in LGAs to water regions (proportion of water use in an LGA that is within a water region), by each sector (*s*)
W_{tr}^{trt}	treated water flow by treatment type (*tr*) [l/a]

f_s^{con}	fraction of water required that is consumed, by sector (*s*)
f_s^{dis}	fraction of discharged water, by sector (*s*), to be treated
$s_{s,tr}^{trt}$	share of treatment type (*tr*) for water discharged by sector (*s*); sums to unity over *tr*
S	stormwater flow off urban area [l/a]
$f_{u,tr}^{trt}$	fraction of stormwater flow from urban land-use (*u*) to be treated by treatment type (*tr*)
W_s^{dis}	untreated discharge water flow from sectors (*s*) [l/a]
$W_{wr,p}^{exp}$	water exported from a water region (*wr*) by type of transfer (*p*) [l/a]
W_{wrt}^{imp}	water imported to a receiving water region (*wrt*) [l/a]
$s_{wrt,wrf,p}^{tran}$	share of transfer type (*p*) and destination water region (*wrt*) for water exported from a water region (*wrf*); sums to unity over *p* and *wrt*
$l_{wrt,wrf,p}$	loss rate per unit distance of water during transfer to destination (*wrt*) from a water region (*wrf*), by transfer type (*p*) [/km]
$d_{wrt,wrf,p}$	distance of water transfer to destination (*wrt*) from a water region (*wrf*), by transfer type (*p*) [km]
$W_{wr,p}^{imp}$	water imported to a water region (*wr*) by type of transfer (*p*) [l/a]
$W_{b,tr,dis,imp\{s,t\}}^{put}$	water into receiving water body types (*b: ground, river, storage*), from treatment (*tr*), untreated discharge (*dis*), and imported by transfer (*imp*), by sector (*s*) and treatment type (*p*) [l/a]
$W_{\{s,t\}}^{tr,dis,imp}$	water from treatment (*tr*), untreated discharge (*dis*), and imported by transfer (*imp*), by sector (*s*) and treatment type (*p*) [l/a]
$s_{tr,dis,imp,b}^{put}$	share of water received by water body types (*b*), from treatment (*tr*), untreated discharge (*dis*), and imported by transfer (*imp*); sums to unity over water body types (*b*) for each source of water
W_b^{take}	water obtained from water body types (*b*) [l/a]
$s_{b,s,ext}^{take}$	share of water obtained from water body types (*b*), by sector (*s*) and extraction type (centralised or self-extracted) (*ext*); sums to unity over water body types (*b*) and extraction type (*ext*)
f_s^{des}	fraction of water required by sector (*s*) obtained from desalination
$W^{\{b:gnd,riv,dam\}}$	net flow into water body types (*b*): ground (*gnd*), river (*riv*) or storage (*dam*) [l/a]

$W_{y,\{b:gnd,riv,dam\}}^{\{in,out\}}$	separate flows into and out of water body types (*b*): ground (*gnd*), river (*riv*) or storage (*dam*); where *y* can be: sector (*s*), treatment type (*tr*), transfer type (*p*), land-use (*l*); and where *in* can be: natural (*nat*), imported (*imp*), or received (*put*); and *out* can be: exported (*exp*) or obtained (*take*) [l/a]
D	dam (storage) volume at time *t* [l]
$D_{time=0}$	initial dam (storage) volume [l]
f^{bypass}	fraction of river flow (above storage) that is not abstracted to storage
V	evaporation loss from storage [l/a]
R^{dam}	release of water from storage into the river network [l/a]
$W_{out,up}^{riv}$	river flow entering the water region from upstream [l/a]
C_{tr}	capacity of water treatment infrastructure, at time *t* [l/a]
$C_{tr,time=0}$	initial capacity of water treatment infrastructure [l/a]
C_{tr}^{-}	decommissioned capacity of water treatment infrastructure [l/a]
$s_{tr,tl}^{trt}$	share of treatment level (*tl*) capacity for each treatment type (*tr*); sums to unity of over treatment level
E	energy use, total, by the water sector [J/a]
$e_{wr,wr}^{exp}$	energy intensity of water transfer [J/l/km]
e_{tr}	energy intensity of water treatment service [J/l]

Table 2. Key variables targeted for calibration, the data sources used and the calibration steps required

Variable	Data Sources	Degree of Calibration
Major dam levels	Reports from the Murray Darling Basin Commission, Melbourne Water and Goulburn-Murray Water	Collation, Comparison and Categorisation Consolidation, Completion and Consistency
Water use	ABS* Water Accounts 1994-2005 ABS* Censuses of Population and Housing 1976-2001 Victorian Water Report 2003/04	Collation, Comparison and Categorisation, Consolidation, Completeness and Consistency
River basin runoff	Water Victoria: a Resource Handbook State Water Reports	Collation, Comparison and Categorisation
Water system energy use	Australian Bureau of Agriculture and Resource Economics	Collation, Comparison and Categorisation, Consolidation, Completeness and Consistency
Inter-basin water transfers	Water Victoria: a Resource Handbook	Collation
Rainfall	Australian Bureau of Meteorology Rainman V4 © Queensland Department of Primary Industries	Collation

* Australian Bureau of Statistics

Table 3. Indoor water use intensity at 2001 for residential development types derived from end use research (Troy et al., 2005). Separate dwellings are taken as 'low density', 'medium density' encompasses semidetached dwellings, terraces and apartments of less than 4 stories, 'high density' includes all dwellings in apartments greater than 4 stories high. Yearly water use per dwelling is × 0.65 to get indoor water use first

Residential Development Type	Yearly water use per dwelling (litres/year)	Assumed average area (m^2) / dwelling	Indoor Water Intensity (litres/m^2 per year)
Low Density	309 000	300	669.5
Medium Density	251 000	250	652.6
High Density	218 000	200	708.5

Table 4. Transfers by pipe or canal from donating SWMAs (columns) to receiving SWMA (rows). Numbers show the contribution of donating catchments as a proportion of the total water transferred to receiving catchments

From To	Upper Murray River	Goulburn River	Campaspe River	Wimmera-Avon Rivers	Thomson River	Bunyip River	Werribee River	Moorabool River	Otway Coast	Glenelg River
Kiewa River	1									
Broken River		1								
Campaspe River		1								
Loddon River		0.91	0.09							
Avoca River				0.62						0.38
Mallee				0.74						0.26
Wimmera-Avon Rivers										1
Latrobe River					0.95	0.05				
Yarra River					0.84	0.16				
Moorabool River							1			
Barwon River								0.98	0.02	
Lake Corangamite								0.13	0.87	
Hopkins River									1	

Table 5. Summary of data availability for variables in the WAS, providing a comparison of the number of unknowns with the number of equations

Equation number	Good data	Moderate data	Poor or no data
A.1	A_l, R	A_u	$s_{l,d}$, f, c, $W_{l,d}^{nat}$
A.2	W_s^{req}, $a_{s,LGA,wr}$, $B_{u,LGA}$	W_i, $I_{u,LGA}$, r_s	
A.3	W_s^{req}	W_{tr}^{trt}	S, $s_{s,tr}^{trt}$, f_s^{con}, f_s^{dis}, $f_{u,tr}^{trt}$
A.4	W_s^{req}		S, W_s^{dis}, f_s^{dis}, f_s^{con}, $f_{u,tr}^{trt}$
A.5		$W_{wr,p}^{exp}$, W_{wrt}^{imp}, $l_{wrt,wrf,p}$, $d_{wrt,wrf,p}$	$s_{wrt,wrf,p}^{tran}$
A.6		$W_{wr,p}^{imp}$, W_{wrt}^{imp}	$s_{wrt,wrf,p}^{tran}$
A.7		$W_{b,tr,dis,imp\{s,t\}}^{put}$	$W_{\{s,t\}}^{tr,dis,imp}$, $s_{tr,dis,imp,b}^{put}$
A.8	W_s^{req}, f_s^{des}	W_u^{roof}, $W_{wr,p}^{exp}$,	W_b^{take}, $s_{b,s,ext}^{take}$
A.9		$W_{z,gnd}^{out}$	$W_{z,gnd}^{in}$, W^{gnd}
A.10	W^{riv}	W^{riv} $W_{z,riv}^{out}$	$W_{z,riv}^{in}$
A.11			W^{dam} $W_{z,dam}^{in}$ $W_{z,dam}^{out}$
A.12		D, W^{riv}, $W_{out,up}^{riv}$	f^{bypass}, W^{dam}, R^{dam}, $D_{time=0}$, V
A.13		W^{riv}, W_{out}^{riv}	f^{bypass}
A.14	$W_{tr}^{req,dis}$	C_{tr}	$s_{tr,tl}^{trt}$, C_{tr}^{-}, $C_{tr,time=0}$
A.15	E	$e_{tr}, W_{wr,wr,p}^{exp}, d_{wrt,wr,p}$	$e_{wr,wr}^{exp}$,
		~15 unknowns	*~25 unknowns*