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A Water Accounting System for Strategic Water Management

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Abstract This paper describes a water accounting system (WAS) that has been developed as an innovative new tool for strategic long-term water management. The WAS incorporates both disaggregated water use and availability, provides a comprehensive and consistent historical database, and can integrate climate and hydrological model outputs for the exploration of scenarios. It has been established and tested for the state of Victoria in Australia, and can be extended to cover other or all regions of Australia. The WAS is implemented using stock-and-flow dynamics, currently employing major river basins as the spatial units and a yearly time step. While this system shares features with system dynamics, learning is enhanced and strategic management of water resources is improved by application of a Design Approach and the structure of the WAS. We compare the WAS with other relevant accounting systems and outline its benefits, particularly the potential for resolving tensions between water supply and demand. Integrated management is facilitated by combination with other stocks and flows frameworks that provide data on key drivers such as demography, land-use and electricity production.

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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 central Queensland south to Victoria; and there has been long-term decline of rainfall in SW Western Australia. These conditions have affected agricultural production while also impacting significantly the water security of Australia's major urban areas where the vast majority of Australians live. Water restrictions were introduced recently in all of the relevant capital cities (Brisbane, Sydney and Melbourne) and some major storage levels have decreased to levels that may support the cities for only one more year without further rainfall.

The public 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 economic and environmental impacts of broad options for providing future water security of capital cities, such as the 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 (MDB) (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 high-level decision making related to the points above. Part of the response has been the launch by the Federal Government of a National Water Initiative, including a water account report for the National Water Commission (SKM 2006). This national-scope water account undertaken by Sinclair Knight Merz (SKM) provided data on the natural water system in its current state.

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

- by focusing on either supply or demand of water they fail to provide an appropriate system perspective that is, one that considers all flows of water entering, being used in, and exiting the anthropogenic water system; 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 affects across the continental water system.

In addition to these recent water accounts, water resource modelling in Australia continues to develop, based on hydrological models of river systems, groundwater, and water management systems. A range of hydrological models are used in different parts of Australia and for various elements of the water system e.g., IQQM (river management), REALM (water allocation), SIMHYD/Sacramento (rainfall/runoff), MODFLOW (groundwater), CHEAT (farm dams). IQQM is a river basin model generally operating at a daily time-step, and applied in the state of New South Wales (Hameed and Podger 2001). REALM models water harvesting and distribution within a water supply system including rivers, operating at a monthly time-step and applied in parts of Victoria (Perera et al. 2005). Both models are concerned with operational management of water resources, which can contribute to understanding of the water constraint issues listed above. However, they do not provide a comprehensive, strategic overview required by decision-makers needing to understand the impacts of key drivers on the water system and alternative options (such as government policy regarding the creation of new dams, or desalination plants, or the possibility for reducing water demand).

The Water Accounting System (WAS) we describe here has been developed to fill the gap between the operational focus of extant water models and the database systems established in recent water accounts. The WAS is a simulation model and database system, incorporating fundamental process relations designed for policy-makers and planners, rather than specific water resource management or research into complex natural processes. The processes are represented by mass balance identities, as in many other water resource models, but in contrast the WAS does not employ complex mathematical models of hydrological processes that embody assumptions made by the modeller (such as groundwater recharge or evapouration rates of open water). Nevertheless, the water balance relationships in the WAS are more realistic than simple combination by super-position of individual water resource measures, though Loucks and van Beek note that such a simple “Planning Kit” approach using super-position produces only small relative errors when large sets of measures (about 25 over a 100 km river stretch) are analysed (Loucks and van Beek 2005).

The WAS is an “open modelling system” (Loucks and van Beek 2005), where stakeholders must create the inputs of key system parameters or transfer outputs of other models to the WAS inputs. This approach is aligned with the view that it is unrealistic to create an optimal plan due to the range of competing and changing priorities of stakeholders. In terms of decision support systems, the WAS is a “systematic analysis” that provides a database and analysis of the data, but the decision-maker must generate options, select decisions, and implement those decisions (Loucks and van Beek 2005). To facilitate this operation, the WAS calculations are performed in real-time to allow stakeholders to interact directly and efficiently with the system.

The WAS reported here is a type of stocks and flows framework (SFF), which employ difference equations to relate changes in physical quantities within a time step (flows) and the level of a quantity at a specified time (stock), as in system dynamics. Several SFF have been developed previously for exploring the longer term physical sustainability of different development scenarios, for specific sectors of the economy such as fisheries (Kearney et al. 2003; Lowe et al. 2003) and agriculture (Dunlop et al. 2002), and linked to the whole physical economy of a nation (Foran and Poldy 2002; Poldy et al. 2000). The SFF of the WAS is designed to address water constraint issues such as those listed above and provide strategic long-term (extending to 2100) analysis capability for decision support. It addresses questions relating to the natural and built water system and to the demand for water, and importantly, 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 NWC and ABS), as well as other historical data over previous decades.

Additionally, greater value is provided by allowing quantified future water system scenarios to be created and analysed. Some issues where the WAS can and has been applied include:

- impacts of climate change can be explored through a collection of exogenous variables set using climate model output (Turner et al. 2007a);
- physical implications of different allocations that might be described by economic models of water trading;
- water security of capital cities and other areas, can be fully explored in the WAS, including the interactions with the energy system (Kenway et al. 2008); and
- geographical coverage of the WAS could be readily extended beyond Victoria (ideally, nationally) to analyse inter-State management options, rather than using exogenous inputs for cross-border flows.

The WAS can be implemented at various scales and it would be ideally suited to treating the Murray–Darling Basin and national issues (such as the possible development of irrigated agriculture in northern Australia). In a separate approach, a more detailed hydrological model of the Murray–Darling Basin is being developed by integrating numerous models of surface and groundwater flows (O'Neill 2008). The simulation component of the WAS could be applied to other regions throughout the world, since it embodies basic mass-balance identities rather than regionally-specific models of hydrological processes; naturally the calibration of the WAS (see Baynes et al. 2009) with observational data (or outputs of other models) would have to be repeated for each region. For the work described in this paper, Victoria was used for the initial development of the WAS due to interest in the growth of the capital city, Melbourne, and the implications on the water system which clearly extend well beyond its current and future urban boundary.

While the 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 our stocks and flows frameworks. Instead, the 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—that is, a "Design Approach" (Gault et al. 1987) to the management problem as implemented in the specifically designed "whatIf" ® software (whatIf 2008). An important implication of taking this approach is that the WAS, like other SFF noted above, are designed to allow physically unrealistic outcomes (which we call "tensions"), such as negative water storage volumes, to be created in temporary scenarios. This unique approach contrasts with numerous hydrological models available (Loucks and van Beek 2005), particularly those designed for optimisation. As we explain in this paper, this use of tensions is necessary to ensure that socio-economic behaviour and policy choices are exogenous to the WAS. This means that past behaviour and policy is not automatically replicated and consequently there is enhanced capacity for learning about the physical basis of the water system and developing innovative management solutions.

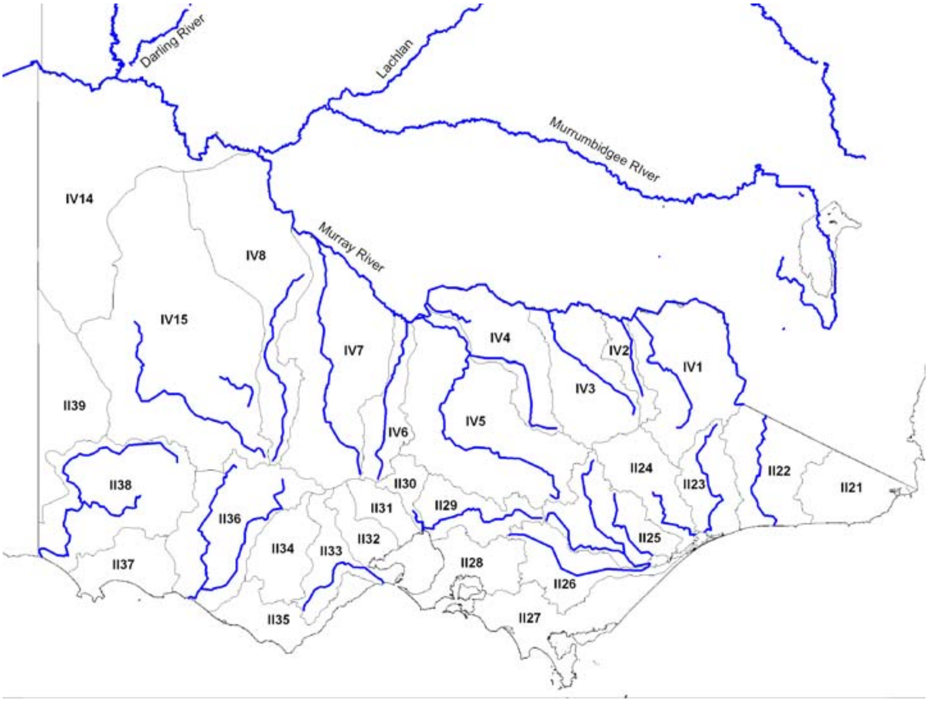

Fig. 1 Major Victorian catchment areas used in the Water Account System, with national ID numbers. The major rivers are displayed, showing the river network associated with the Murray River along the northern boundary of Victoria

Our approach rests on the understanding of the physical importance of resource-based systems, and allows for economic reactions or institutional guidance or any other management construct to be implemented in response to the physical system and aims of society. Consequently, this paper describes, in some detail, the physical relationships in the WAS. We then discuss other important aspects of the WAS, namely: the implementation of the WAS in the “Design Approach”; calibration of the WAS; comparison with other water accounting systems; appropriate resolution; and accounting for water quality.

2 Description of the WAS Framework

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. The spatial coverage of the framework is currently the state of Victoria, with the accounts maintained in each of the 29 water regions (or major catchment basins) that correspond to the Surface Water Management Areas (SWMA[1]) of Victoria (see Fig. 1). The water regions are linked

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[1] Surface Water Management Areas (SWMA) are administrative regions to aid data collection and management of water resources, and they corresponding closely, but not identically, with the catchment boundaries of river systems.

in the framework according to the networks of the river systems. Appropriate geographical connections such as transfers between states are also included.

The framework simulates the natural and anthropogenic water system in 1-year time-steps. Other time-steps (e.g., monthly or seasonal) or spatial resolution could be used without significant development effort. The question of what resolution and time-step to use is related to the intended purpose of the simulation—this question of detail is addressed later in the discussion section. Some measure of water quality can also be presented associated with water use and treatment simulated in the WAS.

The following sections describe the calculations in the individual modules of the WAS framework in some detail. The collection of individual modules is shown in Fig. 2, which is summarised here to provide context for the subsequent detail (Appendix summarises the key WAS calculations in equations).

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

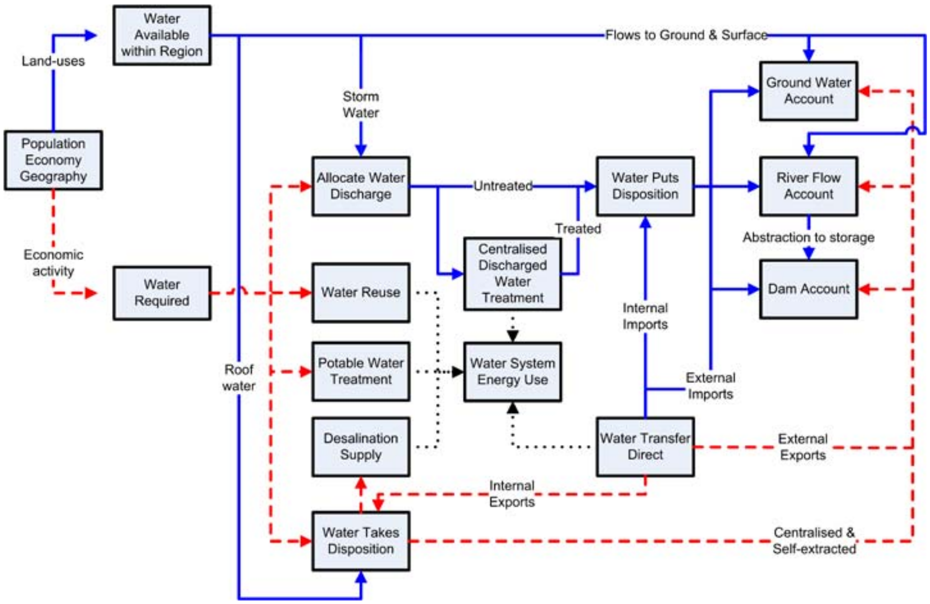

Fig. 2 Schematic diagram showing the high level structure of the water account in the Water Accounting System. The actual stocks and flows calculations are contained in the *boxes*. *Arrows* show connections of data flows (not always the same as water flows) between the modules; *blue* (*solid lines*) represent data on water availability, *red* (*dashed lines*) represent data on water requirements, *black* (*dotted lines*) represent data on energy requirements of the water system

what discharged. Lastly 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.

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 evapotranspired (ET) water in the Water Available within Region 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 effect of rainwater tanks is to reduce both stormwater flows and the net demand for water from dams, rivers and ground. This is calculated in the Water Takes Disposition module which also determines what flows of water will be supplied from the Desalination module. 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. Also contributing to this calculation is the exogenously defined Water Transfer Direct module which determines what flows occur 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 such 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. This module also incorporates the river and dam network in terms of the hierarchy of river basins and tributaries.

Almost all of the modules have exogenous input variables, while appropriate outputs of modules are the inputs to linked modules (as described below and shown in the on-line figures). Access to the data contained in all of the multi-dimensional variables is provided through the diagrammatic interface of the WAS (see on-line figures) in the whatIf software. The user can adjust one, many or all of the exogenous inputs to create a scenario. This can be done manually, with graphical, tabular or Excel spreadsheets interfaces. More efficient setting of inputs can be provided by code scripts written for specific operations, for example, extrapolations of historical data based on past values or trends. Typically, several base scenarios are created from such operations; subsequent scenarios can be built up from combinations of previous instances of inputs.

The water simulation of the Victorian SFF is not a detailed hydrological model in comparison with the integrated models of the MDB Sustainable Yields Project

(O'Neill 2008) (which overlaps the northern water regions of Victoria). It does not, for instance, directly model the interplay between stocks of soil, ground and surface water. Instead, it is better described as an accounting or mass-balance process. 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 (O'Neill 2008) while using the WAS to understand critical drivers and determine strategic water management directions. It tallies up the water availability and the water requirement separately so that tensions can be observed in the river, storage and groundwater systems, locally and across water networks. These features of the WAS are suited to its intended purpose of supporting decisions related to the strategic, long-term future of the water system.

Importantly, no assumptions or optimisations are made within the framework about how various tensions such as storage deficiencies are to be solved. Such assumptions or responses must be provided from outside the WAS, as inputs to it. Those using the framework can trace back to the various causes of such tensions and explore many of the alternative ways to resolve these. This is most simply demonstrated by the possibility, for example, of temporarily creating negative volumes of water storage, that is, a physical "tension" (Gault et al. 1987) that must be resolved by people interacting with the framework to produce a physically feasible scenario. Tensions may be resolved by manual exploration and/or algorithmic procedures (potentially including feedback) associated with the framework.

This "Design Approach" (Gault et al. 1987) feature of tension exploration is discussed further in Section 3. While the concept is relatively simple, it is also somewhat different from common system dynamics and similar modelling approaches. Several advantages follow from this different approach. Firstly, ideological bias is removed from the WAS since particular opinions or positions about how a water system should be managed (operational rules) are not built into the calculations, that is, all behavioural/policy choice is exogenous to the WAS. Instead, the WAS calculations are focused on largely irrefutable accounting relationships reflecting mass-balance. However, a second strength is that it is possible to test a wide range of opinions and proposals since there are many inputs to the WAS that encompass behavioural, engineering and technological change. Thirdly, the linear structure of the WAS arising from the Design Approach substantially enhances learning and understanding since physical cause-and-effect paths are more readily traced. Fourth and finally, this linear structure does not preclude complex and non-linear outcomes being calculated from the WAS, through external interactions (manually or coded) that change inputs to the WAS after observing the outputs.

The detailed description of each module in the next section provides the basis for general features of the WAS to be discussed in Section 3, starting with how the Design Approach is implemented in the WAS. Then the incorporation of historical data into the WAS, that is, calibration, is briefly described (since more detail is provided elsewhere Baynes et al. 2009). It is relevant then to compare the WAS with other water accounting approaches. The final sections of the Discussion review the question of what level of detail and factors should be included in a water account in order to meet the objective of providing planning support for strategic long-term water resource management. This means being able to explore all options in scenarios of water demand and supply. A multi-decadal time-frame is required commensurate with the long-lived nature of water system infrastructure. It should include factors beyond direct water system management but which influence the water system, such as land-use, population growth and climate change. Likewise, the energy requirements and greenhouse gas emissions of the water system are not necessarily trivial (Kenway et al. 2008).

2.1 Natural Availability of Water

The two WAS modules described here calculate the water that becomes available to ecosystems and human use via rainfall.

2.1.1 Building Space Area

The area of built land influences how much water is potentially available from collecting roof water. This component simply converts output from a Victorian Regional SFF (Turner et al. 2007b) about the use of land area across Victoria into roof area that could be used. It also provides the floor space of buildings as an input to the calculation (described later) of water use in and around buildings. (See Fig. 1 of Electronic supplementary material).

2.1.2 Water Availability Within Region

This module is a key component to the water accounts. It incorporates information on the annual rainfall volume over Victorian land uses and partitions this volume into the various environmental flows (See Fig. 2 of Electronic supplementary material). This calculation is done for each water region (denoted by the index 'wrv'). Water that is made available by transfer from another region by pipe or canal is dealt with in a subsequent module ('Water Transfer Direct').

The calculation begins by specifying the land-use in each water region across Victoria. This information is sourced from other frameworks (the Victorian Regional SFF and the Australian SFF Foran and Poldy 2001; Poldy et al. 2000) that deal primarily with Victorian demography and agriculture. Since the land-use is presented in these SFF by Local Government Areas (LGA) it is necessary first to convert or map this data to the Victorian water regions.

Rainfall indicative of a water region and specified in typical units of mm/year is combined with the land-use data to form a volume flow. Some of this flow is potentially intercepted by roof water collection, and this portion informs subsequent calculations of the source of water required (in 'water takes disposition').

The roof water volume is also subtracted from the rainfall volume before considering how the remainder is partitioned between the various environmental flows. A major environmental flow is the water that evaporates or is transpired back to the atmosphere; in Victoria this is approximately 85% of the total volume of rainfall (DRW 1989). The remaining water either eventually ends up in surface water flows such as rivers, wetlands and stormwater, or the ground water bodies i.e., aquifers.

The partition into the environmental flows is done using a single share variable that is exogenously specified. The partition can be different for each water region and land-use type, and can change over time. Ideally this share is informed by hydrological knowledge or models (e.g., Zhang et al. 1999, 2003), and incorporates hydrological effects such as the "base flow" movement of water in sub-surface soils and aquifers into rivers and wetlands. The share variable has been calibrated for the historical period using data on runoff volumes, rainfall and land-use—more detail is provided in Baynes et al. (2009).

The average proportion of rainfall volume that enters the ground water system is typically quite small (Zhang et al. 1999), being about 1% of total rainfall across Victoria (DRW 1989). The flow is passed to the module on 'ground water flows' where it is part of the input and output flows from this body of water.

Flows of stormwater are derived from the surface water that occurs on built land and is not captured by rainwater tanks. The stormwater flow is passed to the module 'Allocation of Water Discharge' where the potential for treating and using this flow is determined.

The remaining surface water flow is totalled over the land-uses in the region and passed to the 'River Flow Account' module where it is consolidated with other "puts" into the river system. Similarly, stormwater flow may end up in the river system depending on whether it is treated or not and subsequently where those flows are directed (they could be to rivers, ground or dams/reservoirs).

Long-term climatic influences can be incorporated by changes to several input variables including the rainfall flow and the 'net rain water destination share' parameter that describes the partition of surface, ground and evapo-transpiration. Annual and longer term variations in these (and other) inputs can also be entered. This is appropriate for analysing elsewhere in the WAS the balance between supply and demand over decades and the associated major storage infrastructure needed, as well as other supply options.

The current framework is not designed to analyse events such as specific intense rain events that might occur on daily timescales. This would be important for understanding, for example, the stormwater infrastructure required to cope with water flows that are significantly greater than the average daily flow for a year. A simple modification to the framework for incorporating this facility might be to use an exogenous input variable that describes the ratio of maximum daily flow to the average.

2.2 Demand for Water

The two WAS modules described here calculate the demand for water from the economy.

2.2.1 Water Requirement

This module largely consolidates the water required by various sectors of society in each water region (river basin). (See Fig. 3 of Electronic supplementary material). The sector breakdown includes the substantial demand from domestic use for both indoor (e.g. washing) and outdoor (e.g. garden) use. This is calculated on the basis of water use intensities expressed as average annual volume of water used per unit area of floor space and land parcel areas. The actual floor and land areas are provided from a separate SFF that deals with demography and land-use plans by the 79 Local Government Areas (LGA) in Victoria, or can be entered independently.

Water requirements from other sectors (e.g., agriculture, industry and electricity generation) are also specified as exogenous inputs. These inputs match variables in other SFF so that outputs of the scenarios developed in these separate simulations can be used as inputs for the WAS. Agricultural water use is specified across the 11 Statistical Divisions (SD) in Victoria. Electricity generation is simulated for each LGA, while other industrial and mining water use is located either within the Melbourne SD or beyond the capital city. This broad account is spread to the LGA using the more detailed land-use stock variable.

To convert data between different geographical units, such as the water requirements in LGA to those in water regions, the WAS uses input parameters called "mappings". The mapping specifies in this case, for each water region the proportion of water requirements that arise in each LGA that overlaps the water region. These mappings are not necessarily generated by the area overlap of the geographic units, since for example, some irrigated agriculture in an SD may be known to occur in a particular water region even though the SD spans more water regions. Further detail is provided in (Baynes et al. 2009). The mapping may change with time to allow changing land-use and location of water requirements to be represented.

The final water requirement variable represents the water that would be taken from some part of the water system in each yearly time-step based on the economic activity assumed in each water region. If some activity is re-using water then less water is required to be taken from the water system; this adjustment is calculated in the next module.

Similarly, when water has been used it may be consumed and not effectively returned to the water system, or it may be discharged to the water system. Hydroelectric plants for example have large water volume requirements from rivers, and large discharge to rivers. These aspects are handled in the modules dealing with choice of water source and destination below.

2.2.2 Water Re-use

Re-use of water in the SFF WAS refers to local or distributed water processing by the economic activity using the water. For example, it would represent cleaning water which is used by manufacturing industries and collected and processed on-site to remove contaminants so that the processed water can be used repeatedly. This concept can be applied in principle to all activities using water, including agriculture where excess runoff could be collected for use by another crop within the water region. (See Fig. 4 of Electronic supplementary material).

Consequently in the WAS, re-use is not the same as recycling of water, which refers to treatment of discharged water by centralised plants, and the treated water then potentially made available to any water use sector and for environmental flows. This is dealt with in subsequent modules ('Allocation of Water Discharge' and 'Centralised Discharge Water Treatment') once the volume of water discharge is known.

The calculations in the water re-use module give the volume of water re-used so that the energy required can be calculated. The ratio of water re-used relative to the actual water required (i.e., total water used less re-used water) by the different activities is specified. In the current version, the exogenous inputs of water requirements must be adjusted externally. This is to align the WAS water requirements with the other SFF (for Victoria and Australia), so that these SFF supply the exogenous water requirements. Future development of the WAS could incorporate the re-use feedback explicitly when the WAS is integrated with the other SFF.

2.3 Determining the Water Source and Destination

The modules described here mostly set the types of water body (storage, ground, or surface) to which water is added and from which water is obtained—called “puts and takes” respectively in the WAS. Other flows are also covered. The set of water bodies covered in the WAS is summarised in Table 2. Only storage is treated as a stock; it is an aggregate over all human and natural storage (e.g., wetlands, lakes and snowpack) within a water region. Flows to and from the atmosphere, surface water, ground water and the sea are included. Surface water in the WAS is an aggregate of natural flows on the landscape surface, that is, rivers. Human transfer of water via pipes and channels, as well as stormwater from built areas, is treated separately. Soil water is implicitly treated as transient between surface water, ground water and the atmosphere (as described above), making it water that is accessible to roots of plants. Ground water is that below the landscape surface that can be accessed by direct human abstraction (wells or pumps). The puts and takes in this WAS are covered in the ‘Allocation of Water Discharge’, ‘Water Transfer (Direct)’, ‘Water Puts Disposition’ and ‘Water Takes Disposition’ modules.

2.3.1 Allocation of Water Discharge

This module introduces water quality into the WAS. Water that has been used and potentially polluted is calculated to determine flows of discharged water to the environment and flows of water that are to be treated (see Section 2.4.2). The two main data inputs from higher in the WAS hierarchy are the water required by each sector and in each region, and the storm water flow off the different built up land-uses. (See Fig. 5 of Electronic supplementary material).

Of the water required, some proportion is actually consumed in the sense that the water cannot subsequently be made available (within the year time-step) to any part of the water system. This includes water that is physically or chemically incorporated in manufactured products such as food, but also includes water that evaporates during use of the water, such as in irrigated agriculture. (For dry-land agriculture and forestry, evapo-transpiration is separately accounted for in Section 2.1.2.)

Water not consumed becomes discharge water, which can be allocated to be treated as either “grey” or “black” water. It is possible for sectors to produce discharge of both classifications, such as households producing grey-water from washing activity and black-water as sewage. The volume of discharge water set to be treated drives the requirement for treatment plant and energy use, calculated in subsequent modules.

The portion of discharge water that is not to be treated will be returned to the environment, and how this occurs is dealt with in ‘Water Puts Disposition’.

Stormwater can also be returned to the environment or directed to treatment facilities in addition to grey- and black-water.

2.3.2 Water Transfer Direct

In addition to water available locally, water can be sourced from beyond the water region or river basin. This module deals with such transfers of water via built systems of pipes and canals. (See Fig. 6 of Electronic supplementary material). Transfers can also be made through the river network connecting water regions and this is dealt with subsequently in the ‘Dam Account’ module.

The movement of water between regions, and exchange with other States, is entirely exogenously specified. The total water imported to a region is set and a parameter used to establish the proportion that comes from the source regions and by type of channel, that is, pipe or canal (the share variable must equal one when summed over both source regions and type of channel). Combining the volume moved with the distance of pipe or canal and a loss rate (in litres lost per litre moved per km) gives the volume of water lost by evaporation and seepage for canals or leaks for pipes. Consequently the water originally exported from the source region can be calculated. The volumes of water exported and imported are provided to the modules that deal with takes and puts from the different water body types.

The energy required for moving water between basins is calculated in a later module (see Section 2.4.4). Future pipeline and canal infrastructure could also be estimated based on known existing water transfer networks and information in planning documents.

Transfers also occur between States, e.g., a substantial part of the Snowy River flow in Victoria is piped to NSW as part of the Snowy Hydro Scheme. The current accounting treatment of inter-state transfers is simpler than for inter-region movement. This is because the transfers largely allow for extractions from the inter-state border, principally the Murray River, and losses are small compared with the extraction. We have also assumed that water imported to Victoria is delivered to either storage or the surface (river) system, while exports from Victoria could be from storage, surface or groundwater; this information goes to inform the respective flow accounts. Similar partitioning of water flows between the water body types is established in the following two modules for all other types of flows.

2.3.3 Water Puts Disposition

In order to perform the final balances of flows to groundwater, river and storage it is first necessary to partition the various demand and supply flows into these three water body types. This ‘Water Puts Disposition’ module achieves this partition simply by applying exogenously specified shares which describe what proportion of flows go into groundwater, surface water or storage. (See Fig. 7 of Electronic supplementary material). The flows are all anthropogenic: discharged water, whether treated or not; stormwater; and transfers from other water regions. Disposition of water in the natural system was determined earlier (Section 2.1.2).

2.3.4 Water Takes Disposition

This module specifies where water for use in the economy is obtained. While the structure of this module is similar to that of the ‘puts’, it is first necessary to account for water that might be supplied from alternative sources. (See Fig. 8 of Electronic supplementary material). One potential source is desalination of sea water while a second is decentralised roof-based collection of rainwater. The latter was calculated in Section 2.1.2 and can be subtracted from the water required. The flow of desalinated water is specified as a proportion of the water required; the desalination flow is subtracted from the water required to identify the water required from desalination plants.

The net water required is considered to be sourced either through a centralised system or by self-extraction from storage, rivers and ground water. The source of water varies with location: in south-west Victoria, for example, a greater proportion is sourced from ground than in the East Gippsland area where most water is extracted from the surface. Centralised abstraction refers to processes that typically make water available through a distribution system to a range of uses. Self-extracted represents water abstracted for own use by households or single enterprises and includes industries such as agriculture sourcing water from rivers, aquifers and runoff captured in small storage. This reduces the requirement for distribution system infrastructure and energy use.

Finally, the water body from which water exported from a water region to another is specified. The subsequent flows of water transferred and the water sourced for use within the region are provided to the groundwater, river and storage accounting modules.

2.4 Infrastructure and Energy Requirements

The modules ‘Potable Water Treatment’, ‘Centralised Discharge Water Treatment’, ‘Desalination Water Available’, and ‘Water System Energy Use’ in this section deal with the infrastructure and energy required to deliver water that is treated and pumped. The volumes of such water have been determined from previous calculators, particularly ‘allocation of water discharge’, ‘water required’ and ‘water takes disposition’.

2.4.1 Potable Water Treatment

Of the water required by the population and all forms of economic activity, only a proportion is required to be supplied at potable standards. This proportion is specified as a share for each water use type within each water region. (See Fig. 9 of Electronic supplementary material). The energy required for this process is calculated from the volume of potable water in the ‘water system energy use’ module.

The total potable water required in each region also drives the stock of treatment plant necessary to treat water to potable standard. Plant capacity increases to meet increased demand and runs at full capacity in these situations. It is also possible in this module, and in calculations of other treatment infrastructure described below, for the capacity to be under-utilised if demand decreases and plant is not retired. However, the stock dynamic calculation allows plant to be decommissioned.

2.4.2 Centralised Discharge Water Treatment

This module deals with potential treatment of water that has already been used and therefore determines the recycling plant capability. It includes the treatment of sewage. The treatment capacity determined in this module differs in concept from the re-use of water because re-use is considered to be undertaken on-site by the industry or sector that first used the water, while recycling occurs in a centralised fashion where the treated water is made available for use potentially by all industries or sectors. (See Fig. 10 of Electronic supplementary material).

The calculation allows black-, grey- and storm-water potentially to be treated to primary, secondary and tertiary water standards. The proportions of different treatments depend on a share variable that represents a policy choice. For example, if an electricity power plant required grey water to be treated to a tertiary standard, then a share of centrally treated grey water from a particular location, destined for that plant, will be treated to tertiary level. These different water types and standards are effectively defined in terms of the intensity of inputs for the treatment plant capacity e.g., how much energy is required to treat a polluted water type to a given standard per unit volume of treated water. This is calculated in the 'water system energy use' module on the basis of the capacity of treatment plant used.

The capacity of the treatment plant is determined in a similar fashion to that of potable water treatment, on the basis of specifying the proportion of new plant that treats to different standards, and decommissions of plant.

2.4.3 Desalination Water Available

One potential way to supply water is to desalinate sea water. This module calculates the stock of desalination plant required based on the total demand for such water within a water region. The type of desalination technology is chosen by specifying the share of new plant using different technologies. In the current version reverse osmosis and evapouration are allowed. Plant can also be decommissioned. (See Fig. 11 of Electronic supplementary material).

Selection of which type of desalination plant supplies the water is directed by specifying a priority for the different technology types. Higher priority plant are used first, and if this plant does not have sufficient capacity to supply the total regional desalinated water then lower priority plant are used.

The amount of plant capacity actually used is passed to the 'water system energy use' module.

2.4.4 Water System Energy Use

This module calculates the amount of energy required to reuse water, supply water of potable standard, treat discharged water of different quality, desalinate sea water, and to transfer water between river basins. The various water flows have been determined previously so the calculation essentially involves multiplying these flows with energy intensities. (See Fig. 12 of Electronic supplementary material).

In the case of water transfers it is useful to include the distance of the transfer, so the intensity is expressed as J per km per litre. The WAS does not incorporate a GIS or elevation-based model of the transfer energy intensity, though such features could be included. The complexity of explicitly incorporating this in the WAS for all possible transfer combinations—and including other factors such as frictional energy loss—is likely to outweigh any benefits. Instead, a practical approach was adopted of allowing for input of transfer intensities and distances, which are calibrated using historical data and can be modelled for specific cases outside the WAS as necessary.

2.5 River, Storage and Groundwater Accounts

This section describes the accounting balance between water supply and demand covered by the 'Ground Water Flows', 'River Flow Account', and 'Dam Account' modules.

2.5.1 Ground Water Flows

In the current version, ground water is accounted for by aggregating extractions and inputs to the ground water system. (See Fig. 13 of Electronic supplementary material). Subtracting total extractions from inputs within a water region allows comparison with quoted sustainable yields. More advanced treatment of the groundwater system is technically possible from a modelling perspective (O'Neill 2008), and relies on better knowledge and data of the dynamics. Transfers between groundwater and surface flows may result in interstate flows and occur over decades or centuries. It may be necessary for instance to incorporate stocks of groundwater that exist at different depths, vary widely in area, and interact or have recharge at rates that span many time periods.

2.5.2 River Flow Account

This account balances the inputs and outputs within each water region from the natural surface water system (rivers). (See Fig. 14 of Electronic supplementary material). The inputs and outputs arise from human or economic activity, as well as runoff from rainfall. At this point in the hierarchy of module calculations the balance (or net river puts) is a partial net flow because interactions with a region's water storage have not been included and the cumulative flow of water down the river network of tributaries has not been calculated. It is possible for this net flow to be negative, if losses from the river are greater than gains. Interactions with the regions's water storage, and water regions connected by the river network, are incorporated in the calculations of storage level in the subsequent 'Dam Account' module.

2.5.3 Dam Account

Briefly, the total water potential 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. (See Fig. 15 of Electronic supplementary material). Storage and other water bodies (i.e. the river and groundwater system) in a water region are treated as a total or aggregate for that region.

This module begins by consolidating the water volumes taken from and delivered to the dam that have been determined in modules higher in the hierarchy. This partial net flow to dams however excludes several important flows associated with the environment.

One of these flows is losses due to evaporation from the water surface—this is calculated next using specified surface area and evapouration rates. Models of the variation of evaporation rates with storage volume (or area) could be included in the framework, which would require an iterative calculation. This was omitted in this version because suitable dam evapouration models were not assessed at the time, though using exogenous input of area and evaporation rate allows the flexibility for such calculations to be made outside the framework.

The other key flows that are subsequently calculated are the water diverted from the river system to the region storage, and conversely the water released from the storage into the river system in years when natural water availability downstream is less than sufficient for water dependent activities. 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 (Fig. 1). Calculation of diversions to storage further down the river network account for this cumulative flow using the matrix mathematics available in the whatIf software. The river network is specified efficiently using a vector (one-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. The software allows this vector to be 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.

Calculation of water released from upstream storage is handled by a similar algorithm just described for diversions from river flow to storage. The net affect gives the flow anywhere along the river network, as well as the flow captured in storage. This completes the inputs to and outputs from water storage, and the evolution of the dam volume can be calculated by integrating the balance of inputs and outputs over time.

The ‘Dam Account’ module then reports the volume of storage relative to the specified capacity in each region. It is deliberately possible in this framework for the volume of (potential) water storage to be negative or to exceed the capacity (see Fig. 3 for examples). Either case is a physically unrealistic tension, and the calculated water storage represents a potential volume, rather than an actual one. In order for the volume to be realistic, tensions must be resolved by adjusting suitable controls in this module or higher up the hierarchy (see next section). A similar accounting scheme occurs for the river flow leaving the water region, which can be positive or negative and is also reported in this module.

Two examples of tensions in storage volumes are illustrated in Fig. 3, where the volume of stored water in three strategic water regions of Victoria (with the four largest dams in Victoria) are shown over the historical period and for an illustrative scenario. The total storage capacity in each region is also shown. There cannot be physically unrealistic tensions in the historical period, so the storage level is always positive and less than the storage capacity. The historical levels displayed reproduce the observed data acquired in the calibration process (Baynes et al. 2009). The illustrative scenario represents a range of assumptions, including:

- expected population growth in Victoria;
- agricultural water consumption and per capita domestic water consumption that is constrained to contemporary levels;
- typical inter-region transfers;
- river abstractions to storage that are a constant percentage of river flow;
- constant storage capacity; and
- a climate change scenario of 2.2°C increase in global temperature by 2050 (Jones and Durack 2005).

Under these illustrative settings, the storage level in the Upper Murray water region (IV1 covering the Dartmouth Lake and Hume Reservoir) stays physically feasible for the scenario, rising for several decades before declining at an increasing

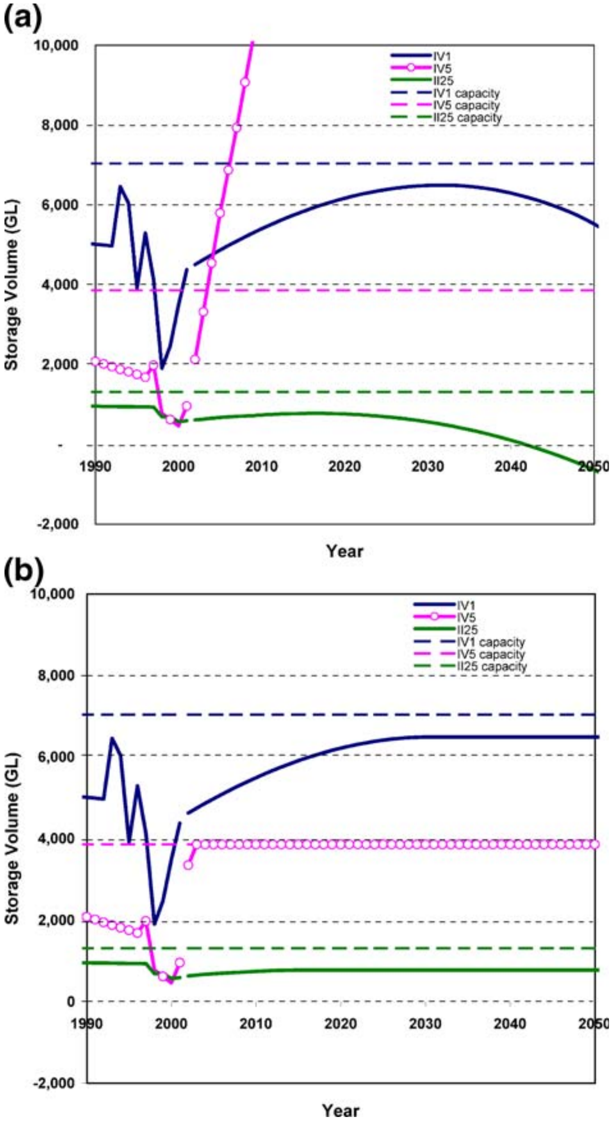

Fig. 3 Storage volume (*solid lines*) compared with capacity (*dashed lines*) in the strategic dams of Victoria (IV1 Dartmouth Lake, Hume Reservoir; IV5 Lake Eildon; II25 Thomson Reservoir). Historically calibrated data is shown (1990–2001). The illustrative scenario starting in 2002 involves, among other things, population growth, constrained consumption, typical inter-region transfers, constant river abstractions, and climate change. (**a**) shows the scenario with physical tensions in storage volume; (**b**) shows these tensions resolved (in this case by changing the proportion of river flow diverted to storage)

rate. However, physically unrealistic tensions are observed for Lake Eildon in the Goulburn water region and the Thomson Reservoir supplying Melbourne via inter-basin transfer from the Thomson water region. The calculated storage of Lake Eildon exceeds the capacity, while the Thomson Reservoir has a negative level after 2040 in the scenario. Clearly, either case cannot physically occur so that the tensions must be resolved for the scenario to be feasible. This requires the user to explore the data in the WAS to establish the key flows, factors and assumptions leading to the tensions. From the list of selected assumptions above and the description of the WAS it is evident that there are many potential influences on storage levels, and related outputs such as river flows, ground water flows, and energy use in the water sector.

Note also, that other tensions may also exist (even if there is surplus or realistic storage levels) such as diminished or negative river flow. Additional tensions may also arise while attempting to resolve the first tensions.

In the example of Fig. 3, the river by-pass fraction can be adjusted—increased for Lake Eildon, and decreased for the Thomson Reservoir—to maintain storage volume. It would then be necessary to review the impacts on river flow (indeed, for the Thomson River under the illustrative scenario, the dam can be maintained, but the river flow ceases by the end of the century). The additional "view" code or script that was used to achieve stable and physically realistic storage volumes could be incorporated into the WAS directly so that negative or excessive storage volumes do not occur. However, doing so would obscure the possibility of achieving the same end result, that is, alleviating tensions such as unrealistic storage levels, by adjustment of other factors of influence. Some of the potential factors in the current example are identified in the selected assumptions given above.

The multiplicity of possible controls (i.e., inputs) throughout the WAS that could be used in combination to alleviate such tensions suggests that direct human interaction is an efficient way to resolve the tensions. This is the intended manner in which the WAS has been designed to be used for decision support. This allows for potentially innovative solutions to be developed that may involve:

- behavioural choices relating to water use and environmental flows;
- as well as engineering responses like adjustments to dam capacity; and
- technological progress such as water saving efficiencies.

Since this sort of "decision space" feedback is not hardwired into the code of the simulation framework it facilitates an understanding of interactions in the water system and the search for novel solutions to water constraints as a participatory approach (Silva-Hidalgo et al. 2008). This is a point of difference with common "system dynamics" (SD) approaches to water resource management (Winz et al. 2008). Clearly, the WAS employs SD stock-and-flow relationships similar to that illustrated in Fig. 2 of Winz et al. (2008), but we exclude from the calculation code any human responses that are often incorporated as feedbacks in SD models, such as public awareness of polluted rivers driving construction of water treatment facilities as illustrated in Fig. 1 of Winz et al. (2008). In the WAS, the understanding created via exploration is greatly enhanced by the linear structure of the WAS, which is part of the Design Approach discussed in the following section. Importantly, despite this linear structure, complex outcomes may result from the multiple feedbacks created by users interacting with the WAS (rather than from within the WAS).

3 Discussion

The discussion in this section of important aspects of water accounting relates strongly to the purpose of the WAS. The WAS is intended to support decisions related to the strategic, long-term future of the water system, such as impacts on water supply and environmental flows of population growth, alternative economic activity, technological innovations and climate change. The potential of the WAS to successfully support strategic decision-making is evaluated in Table 1 in terms of features suggested by Silva-Hidalgo et al. (2008) and Winz et al. (2008). Most of the

Table 1 Evaluation of the WAS in terms of desirable features for decision support systems in water resource management

Features suggested by:		Self-assessment of the WAS
Silva-Hidalgo et al. (2008)	Winz et al. (2008)	
Integrality	Scoping	Good—integrated with other multi-sector stock and flow frameworks (especially population, land-uses, economic activity, electricity generation)
Representativity	Parsimonious	Good—resolution of the WAS limited to a lumped model of river basins; groundwater dynamics and water quality modelling excluded (see Sections 3.4 and 3.5)
	Confidence	Good—enhanced by the reproduction of historical data (see Section 3.2); transparency of all data and code
	Learning	Good—enhanced by the linear structure of the Design Approach of the WAS (see Section 3.1)
	Support	Poor—early attempts to involve state government stakeholders were not successful; better opportunities are presented by continued need for a national water account
Flexibility	Revisions and updates	Good—supported by modular and linear structure (see Section 3.1)
Accessibility	Communication	Good—software provides easy access to all data via a diagrammatic interface; supports scenario creation, comparison and analysis

features appear positive, and in the following sub-sections we explore key aspects in more detail. However, it is beyond the scope of this paper to determine the reasons why early attempts to involve stakeholders and secure support from management were limited, but we note that our recent involvement in Australia's National Water Initiative provides further opportunities.

3.1 Implementing the WAS as a Design Approach

The linear structure of the water account broadly reflects the separation of "demand" and "supply" of the "Design Approach" (Gault et al. 1987). The supply of, and demand for, water are specified separately. Supply is ultimately determined by the 'water availability within region' module while demand is largely specified by the 'water requirement' module. This separation of demand and supply and the linear structure of the WAS is illustrated in Fig. 4 where data connections from one module to another are indicated by arrows. For example, different data derived in the 'water availability within region' module is passed directly to the 'allocation of water discharge', 'water take disposition', 'river flow account' and 'ground water flow' modules. (These data connections are shown in the diagrammatic interfaces (see figures in the Electronic supplementary material) by yellow tags with module names on variables). Key data influences have also been noted above in the description of the WAS modules. The data flow connections have been organised in Fig. 4 so that

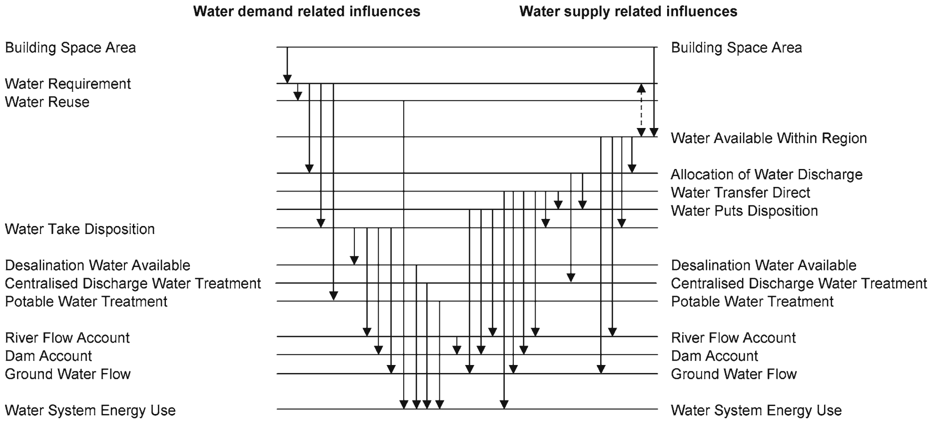

Fig. 4 Data flow between the framework modules indicated by *arrows*. The data flow connections have been grouped together according to the modules where the data originates. *Arrows on the left* are generally associated with data about demand for water, those on the *right* with supply or availability of water

those on the right side of the diagram relate to supply of water and those on the left to demand for water.

As noted above tensions may arise due to differences ultimately in the settings of water demand and supply. Tensions typically manifest in lower modules, especially in the 'dam account' and 'ground water flows' modules. The way in which the linear data flow within the WAS facilitates understanding of the water system and the resolution of tensions is illustrated in Fig. 5. In Fig. 5, the data flow connections have been grouped together according to the modules that receive data from higher in the WAS hierarchy of modules. Therefore, the cause of a tension in the 'dam account' module for example, can be traced back up through the framework, starting with the more direct influences such as the water takes and puts calculations and proceeding up the hierarchy to indirect factors. In the situation of Fig. 3 and potential water storage

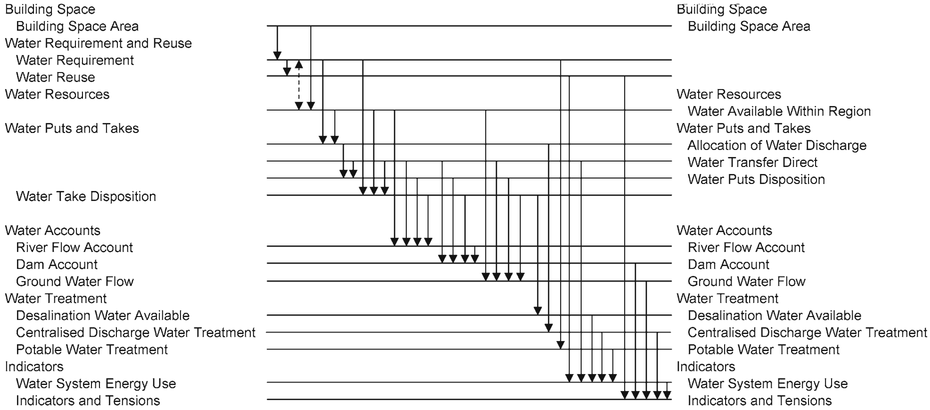

Fig. 5 Data flow between framework modules, organised to emphasize those components of the water account that receive data

tensions, we could for example explore alternatives of reducing water consumption, increasing dam capacity, or utilising inter-basin water transfers. Alternatively, exploration of the inflows and outflows of water storage might reveal that climate change or population growth are the key factors, and subsequent scenarios may be created to analyse the sensitivity of storage levels and river flow on these factors.

In addition to manually resolving tensions, supplementary macro scripts or "views" can be written in the whatIf software application (whatIf 2008). These scripts can simply display collected or manipulated outputs, or they may be written to enter data into the exogenous variables. These scripts can also be used to implement feedback loops that resolve tensions and/or generate scenarios to reproduce specific targets. An example of the use of scripts to realize feedback loops is an algorithm to maintain dam levels by adjusting diversions and extractions from the river network.

3.2 Calibration of the WAS

The WAS has been calibrated over several decades to reproduce a wide range of historical data sets, and is described in more detail elsewhere (Baynes et al. 2009). The calibration is performed in a framework similar to that of the simulation, using the whatIf software. Indeed, the simulation framework is copied into the calibration to provide the "target" variables. Additionally, raw data sets from a wide variety of sources are imported into the calibration. The key variables involved were major dam levels (partially illustrated in Fig. 3), water use, river basin runoff, water system energy use, inter-basin water transfers, and rainfall. The calibration diagram and code then fits the data to corresponding simulation variables. This may be direct where the correspondence is straight-forward (such as rainfall data), or it may involve imputing unknown historical values such that the observed historical data (e.g. dam levels) are reproduced by the simulation.

This process means that all variables in the simulation contain either observed historical data or are consistent with observed data. This provides context for understanding past changes and the foundation for creating meaningful scenarios in the simulation. Additionally, it results in increased confidence in the simulation since it is run over the historical period and reproduces all internally consistent historical data. This outcome does not follow automatically and can be a demanding test due to multiple interactions between factors in the water account. For example, data on energy use by the water sector was obtained from independent sources, but must also relate simultaneously to the amount of water used, wastewater produced, treated and pumped.

The calibration process also identifies where data sets may be inconsistent and records an audit trail of data integration and changes. We adopt an approach of quarantining recognised authority data sets from change (unless significant inconsistencies appear) and imputing data for otherwise unknown variables or correcting or omitting those data sets that are evidently in error. An alternative of representing inconsistencies by residual or error terms is not appropriate in the WAS. Such error terms are useful when dealing with a system that is critically-determined (i.e., equal number of equations and variables) e.g. there are values for all the variables of a single balance equation (Kirby et al. 2008). However, the WAS is under-determined, that is, there are more independent variables than equations involving those variables, so it is possible to get the same model output from different values of the variables (Gault et al. 1987). Substantial resources would be required to be able to provide observed (or confidently modelled) data for the substantial number of variables, and their disaggregation, that is used in the water account. Nevertheless, using a system-wide framework for the water account and related economic activity that comprehensively and consistently covers the interactions between sectors (e.g., land-use, water supply, water use, and energy use) provides additional information in the form of constraints on the range of values that variables can feasibly take.

3.3 Comparison with Other Water Accounting Approaches

In this section, we make a general comparison of the WAS with other water accounting schemes applicable to the Australian context, produced by the ABS and NWC or recommended by the UN. The purpose here is to inform future development of the WAS by identifying key differences and similarities. We show that the WAS brings together use and supply data in keeping with UN recommendations, and provides both historical data and the ability to simulate future scenarios. Other water analysis (e.g., Kirby et al. 2008) may be considered to be water accounting that make use of hydrological modelling and are therefore omitted from the comparison here, which focuses on systems that integrate measured data.

The ABS have a published a small number of water use reports e.g., ABS (2006). The water accounts assembled for the National Water Commission (NWC) were produced for the year 2004–2005 (SKM 2006). The United Nations Statistics Division have recommended a water accounting framework (System of Economic and Environmental Accounts for Water, SEEAW) that integrates the physical and economic data (UNSD 2007). A summary of the characteristics of each water account is given in Table 2, which broadly describes each account in terms of the general analysis features (which are independent of the water context), the availability of natural water (both stocks and flows), and the use of water in the economy.

Table 2 shows that only the WAS is set up for both historical data assimilation and simulation of future scenarios. This important aspect for strategic water management is based not only on the software implementation of the WAS, but also through the explicit connection of the WAS with simulation of economic activity which influences both water availability and demand. All accounting schemes are based around a one-year resolution (though clearly there is scope for higher resolution albeit with greater demands on data). All but the ABS water account provide geographic resolution down to river basin level.

In terms of accounting for water availability, the WAS has much in common with both the NWC and UN accounts; by contrast the ABS data is limited to surface water stocks and flows. The UN system appears to be the only account explicitly including soil water. Soil water is treated in the WAS as an implicit intermediate stock between the atmosphere, surface and ground water, with the end effect that the yearly partition of water between these stocks is the relevant accounting term. Soil water stock is not explicitly included in the WAS since this water is not actually abstracted by economic activity (though evapo-transpiration of soil water is included in the WAS through land-use activities such as agriculture and forestry).

Finer detail on surface stocks, such as off-river storage and small farm dams, is contained in the NWC compared with the WAS. The NWC approach also allows for levels (stocks) of groundwater to be accounted, while this version of the WAS omits

Table 2 Summary comparison of the Water Accounting System (WAS) with other approaches relevant to Australia

Characteristics	System			
	WAS	ABS	NWC	UN SEEAW
Analysis features				
Temporal basis	Fully dynamic; yearly (but could include finer time steps); multi-decade historical time series; multi-decade scenario time series	Static; single year accounts but not every year	Static; yearly	Static; yearly (but recognise potential for seasonal resolution)
Geographic basis	River basins; local government areas (LGA) for economic activity	State level	River basins and groundwater management unit	Recommend river basins or economic management areas
Simulation capability	Scenario creation and analysis; link between economic activity and water system; linked closing and opening balances	No	No (but linked closing opening balances)	No
Availability of natural water				
Stock measures				
Atmospheric	No	No	No	No
Surface	Aggregate basin storage	Major storage	Basin storage, including aggregate small farm dams; on- and off-river storage	Recommended
Soil	No stocks	No	No	Recommended
Ground	No stocks	No	Aquifer within a groundwater management unit (limited data)	Recommended
Sea	No	No	No	No
Flow measures				
Atmospheric	Precipitation; evapo-transpiration (based on land-use activity)	No	Precipitation; evapo-transpiration	Precipitation; evapo-transpiration

Surface	River network; affected by land-use; evaporation losses; extractions and returns	Extractions and returns	River network evaporation; and other losses; extractions and returns	River network; flows to and from soil and ground; extractions and returns
Soil	Modelled as transient between surface, ground and evapo-transpiration	No	No	Flows to and from surface and ground; extractions and returns
Ground	Balance of inflows and outflows; extractions and returns	No	Inflows and outflows; extractions and returns	Flows to and from surface and soil; extractions and returns
Sea	Inflows; extractions and returns	No	Inflows and outflows	Inflows; extractions and returns
Measures of water use by economic activity				
Extraction	Detail by economic activity and LGA; self extracted and centralised; linked to land-use and economic activity	Detail by economic activity; self extracted and centralised	Self extracted and centralised	Recommended; include monetary flows
Transfers	Between river basins and inter-state; evaporation and other losses; energy required	No	Between river basins or groundwater management areas	Recommended; include monetary flows
Treatment	Treatment of fresh and used water to primary, secondary and tertiary standards; energy required; intra-region pumping energy required	No	No	Recommended; include monetary flows
Use	Driven by detail on economic activity and water use intensity	Detail by economic activity	By high-level economic activity	Recommended; include monetary flows
Returns	Driven by economic activity and land-use; quality partitioned into storm-, grey-, and black-water; returns to surface or groundwater only	Reported by economic activity	High-level economic activity returns	Returns to surface, soil or groundwater

"Inflows and outflows" refer to natural water system flows, "extractions and returns" to economy-related water system flows these for reasons described above. Despite the structure of the NWC accounts, data on groundwater stocks and some related flows are extremely limited and appear to be either omitted or taken from unpublished estimates or modelling. Additionally, since the lateral extent of groundwater management units and river basins typically overlap in complicated ways, an accounting structure is required to avoid potential double counting or misallocations of surface and groundwater flows between these stocks.

In terms of the use of water within the economy, the detail in the WAS is closely aligned to the ABS. Uniquely, the WAS links the water use to other accounts and simulation of the economic activity. It also explicitly deals with the treatment of water (before or after use) and the transfer of water outside the natural system. In this way, it links water provision with energy consumption and infrastructure development. The importance of the link between water and energy has only recently been recognised in Australia (Kenway et al. 2008; Neal et al. 2007).

Overall, the ABS provides detail on economic use of water, the NWC focuses more on natural water availability, while the WAS combines both these sides of the water account at similar levels of detail and in a dynamic framework. From the comparison, it would appear that future development of the WAS might benefit from separating storage into on- and off-river storage. The treatment of groundwater stock could also be considered if sufficient data and understanding of the dynamics becomes available (O'Neill 2008). Such treatment must deal with differing spatial extent and temporal dynamics of aquifers and river basins.

3.4 Resolution and Non-linear Effects

The issue 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. 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, so it is necessary to explore their implications on the accuracy of the SFF Water Account simulations.

This version of the WAS uses a yearly time step to simulate averages across the water region spatial units over this time period. Most of the hydrological flows of water (say from precipitation to surface via either rapid runoff or longer term soil "base flow" or snowmelt) will occur within a year.

Likewise, natural river flows can change within a river network at any time scale less than a year (e.g., seasonal, monthly and daily for dam releases, or daily for rain events), but not generally longer. Hence, events such as higher rainfall in 1 year should not affect the natural river flow, i.e., in the absence of on-river storage, further down the river network in subsequent years. When storage systems are included, diversion of river flow to storage systems, and release from storage, clearly connect river flow across years.

We note that timescales of interactions between ground water (aquifer) bodies may extend well beyond the yearly time step, and we have not attempted to model these processes. Instead we have dealt with this part of the water system by simulating flows, not stocks, as described above.

Related to the question of appropriate resolution is the issue of whether sufficient hydrological detail is contained in the water account. The temporal and spatial resolution of the WAS can largely be increased simply by using more elements in the relevant dimensions of the variables (e.g., water regions become sub-catchments). These changes do not generally affect the accounting relationships in the WAS, so its structure and logic remain unchanged. However, the introduction of additional stocks, such as snowpack, may be necessary if finer time-steps are used. Higher resolution has the benefit of more closely aligning with more detailed hydrological models, but involves substantially greater calibration and scenario creation/analysis effort. In contrast with the long-term strategic purpose of the WAS, hydrological details are important when understanding and operating the water system over daily to seasonal timeframes. For example, releases from major dams supplying irrigation activities vary throughout the year and are highly seasonal. Following the application of irrigation water, some proportion will return to the river system via soil recharge or runoff, and the rate of return of water will differ in a potentially non-linear manner depending on the volume of water applied.

For example, consider 100 Gl of irrigation water applied in an upstream region in the dry season (summer in Victoria) with the result that, say, 20% or 20 Gl returns to the river, and compare this to 25 Gl applied in each of four seasons when, say, 16% or 4 Gl returns each season giving a total of 16 Gl for the same total of 100 Gl applied. In this hypothetical example the return volume is different by 20%; of course, a linear relationship between water applied and the return flows in this example would yield no difference in the yearly total. The volume and timing of river flows downstream of the upstream irrigation activity may therefore depend on the volume and timing of water applied. Other modelling and analysis capabilities aim to calculate such finer-scale issues (O'Neill 2008), and it is not the role of the SFF Water Account to duplicate these calculations.

Instead, the results of such finer-scale analysis can be used to set values of the appropriate inputs of the SFF Water Account (such as input variables that describe the discharge from various water uses (see the 'Allocation of Water Discharge' module)). In the absence of such inputs, the SFF Water Account uses empirical data in the calibration process, such as observed river flows and volumes of irrigation water applied, to establish appropriate parameter values for yearly totals. Simulated futures calculated in the SFF Water Account remain accurate if the conditions of the calibration period, such as summer dominated irrigation, continue to apply in future scenarios.

However, future water system conditions may be different from past experience. In the hypothetical example given above, return flows to rivers would be too high by 20% if irrigation volumes were reduced by a factor of four, or if irrigation was used evenly throughout the year. In this case, more accurate simulations may be produced by using finer-scale models to create updated values of input parameters in the SFF Water Account. Such adjustments were made in the case of calculations that involved the effect of climate change on rainfall and evaporation, for example (Turner et al. 2007a).

Alternatively, if such refined inputs are not available, trends can be extrapolated from those of the historical period. Another alternative is to undertake a sensitivity analysis where the overall impact in the water system of linear and non-linear changes to hydrological or other input variables can be explored in scenarios that test the sensitivity of the system to nominal changes in these variables. Past experience with such long-term strategic simulations (Foran 2003; Foran and Poldy 2002; Turner et al. 2007a, b) has demonstrated the relatively small effect of finer-scale issues when compared with exponential growth in overall consumption. For example, a growth rate of 2.5% per annum implies a doubling of impacts in about three decades, which is likely to be a significantly greater change than other factors that do not involve positive feedback.

3.5 Water Quality

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. However, 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, the current framework does not simulate concentration levels of pollutants, or river "health" indicators directly. This aspect could be incorporated in future developments, with appropriate advice. Alternatively, estimates could be made by providing Water Account System outputs to other models.

More sophisticated estimates of water quality, such as concentrations of pollutants or nutrients, have not been built into the Water Account System since the current ability to understand and predict water quality is not well established. This is a difficult area to model due to complex interactions involving chemical and biophysical reactions influenced by residence times and therefore specific flow events. A constructive way to proceed at present is to simply present amounts of nutrients and pollutants entering river systems.

4 Conclusions

A water accounting system has been developed for the purpose of strategic water management i.e. supporting long-term decisions requiring multi-decadal perspectives. The WAS has been applied in the state of Victoria, where it was calibrated to reproduce a wide range of historical observations. The WAS is more of a biophysical accounting system than a detailed hydrological model, that integrates the natural and human elements of the water system. In doing so, it combines the focus of water accounting databases (from the ABS and the NWC), and aligns well with the UN SEEAW (UNSD 2007). It is designed to provide a complete and consistent account of the water system within a geographical region.

Additionally, the WAS provides a capability for simulating future scenarios. This is implemented in a "Design Approach" structure (Gault et al. 1987), where tensions between demand and supply are explicitly identified, but not resolved internally within the WAS; nor is any optimisation built into the core of the WAS. This means that a wide variety of 'what if' scenarios can be created and explored. Examples may include 'what if': climate change is not mitigated and occurs in combination with population growth (Turner et al. 2007a); or different urban-form, water end-use and water supply options are pursued (Kenway et al. 2008); or rural land-use changes to a post-agricultural basis. The impacts displayed by the WAS on water security, environmental flow, and infrastructure and energy imposts might be substantially different. Most importantly, key drivers of the water system can be identified via chains of ‘cause-and-effect’ because of the linear structure of the accounting system.

This learning feature is aided by the transparency of the WAS since all data objects and relationships (including the code representing the mathematics and accounting) are directly accessible in the whatIf software (whatIf 2008). This software also facilitates the creation and management of scenarios. As a consequence of this and the design of the WAS, fewer resources are needed to create and use the accounting system for supporting strategic long-term decision making.

The design of the WAS provides good potential for addressing issues relating to Australian water constraints and possible responses. The impacts of climate change can be explored through a collection of exogenous variables (covering natural and human responses) that are set using climate model output (Turner et al. 2007a). In terms of water trading, while the WAS does not involve prices, it does present the physical implications of different allocations that might be described by economic models. The water security of capital cities and other areas, can be fully explored in the WAS, including the interactions with the energy system (Kenway et al. 2008). The geographical coverage of the WAS could be readily extended beyond Victoria (ideally, nationally) to analyse inter-State management options, rather than using exogenous inputs for cross-border flows. Further developments for improving the WAS have been identified, including the possibility of increasing temporal and spatial resolution, and dissagregation of surface water stocks.

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Appendix

The following set of equations summarise the key relationships embodied in the WAS, where the explanation of the symbols is given in the Notation section. Common subscripts associated with time step and spatial details (water regions, wr) have been omitted for clarity.

Natural availability of water

$$W^{nat}_{l,d} = s_{l,d} R \left(A_l - fcA_u\right) \tag{1}$$

Water required

$$W^{req}_{s} = a_{s,LGA,wr} \left(W_i + I_{u,LGA} B_{u,LGA}\right) - r_s \tag{2}$$

Allocation of water discharge

$$W_{tr}^{trt} = W_s^{req}\left(1 - f_s^{con}\right)\left(1 - f_s^{dis}\right)s_{s,tr}^{trt} + Sf_{u,tr}^{trt} \tag{3}$$

$$W_s^{dis} = W_s^{req}\left(1 - f_s^{con}\right) - W_{tr}^{trt} \tag{4}$$

Direct water transfers

$$W_{wr,p}^{exp} = \sum_{wrt} W_{wrt}^{imp} s_{wrt,wr,p}^{tran} \Big/ \left(1 - l_{wrt,wr,p} d_{wrt,wr,p}\right) \tag{5}$$

$$W_{wr,p}^{imp} = \sum_{wrf} W_{wr}^{imp} s_{wr,wrf,p}^{tran} \tag{6}$$

Water puts disposition

$$W_{b,tr,dis,imp\{s,t\}}^{put} = W_{\{s,t\}}^{tr,dis,imp} s_{tr,dis,imp,b}^{put} \tag{7}$$

where $b = gnd, riv, dam$.

Water takes disposition

$$W_b^{take} = s_{b,s,ext}^{take}\left(W_s^{req}\left(1 - f_s^{des}\right) - W_u^{roof} + W_{wr,p}^{exp}\right) \tag{8}$$

Ground water flow

$$W^{gnd} = \sum_{in,z} W_{z,gnd}^{in} - \sum_{out,z} W_{z,gnd}^{out}, \tag{9}$$

River flow account

$$W^{riv} = \sum_{in,z} W_{z,riv}^{in} - \sum_{out,z} W_{z,riv}^{out}, \tag{10}$$

Dam account

$$W^{dam} = \sum_{in,z} W_{z,dam}^{in} - \sum_{out,z} W_{z,dam}^{out}, \tag{11}$$

$$D = \sum_{time}^{t}\left[\left(1 - f^{bypass}\right)\left(W^{riv} + W_{out,up}^{riv}\right) + W^{dam} - V - R^{dam}\right] + D_{time=0} \tag{12}$$

$$W_{out}^{riv} = f^{bypass} W^{riv} \tag{13}$$

Water treatment capacity

$$C_{tr} = \sum_{time}^{t}\left(W_{tr}^{req,dis} s_{tr,tl}^{trt} - C_{tr}^{-}\right) + C_{tr,time=0} \tag{14}$$

Water system energy use

$$E = \sum_{tr} \sum (C_{tr} e_{tr}) + W^{exp}_{wr,wr,p} d_{wrt,wr,p} e^{exp}_{wr,wr} \tag{15}$$

Notation

$W^{nat}_{l,d}$	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^{req}_s	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^{trt}_{tr}	treated water flow by treatment type (tr) [l/a]
f^{con}_s	fraction of water required that is consumed, by sector (s)
f^{dis}_s	fraction of discharged water, by sector (s), to be treated
$s^{trt}_{s,tr}$	share of treatment type (tr) for water discharged by sector (s); sums to unity over tr
S	stormwater flow off urban area [l/a]
$f^{trt}_{u,tr}$	fraction of stormwater flow from urban land-use (u) to be treated by treatment type (tr)
W^{dis}_s	untreated discharge water flow from sectors (s) [l/a]
$W^{exp}_{wr,p}$	water exported from a water region (wr) by type of transfer (p) [l/a]
W^{imp}_{wrt}	water imported to a water region (wrt) [l/a]
$s^{tran}_{wrt,wr,p}$	share of transfer type (p) and destination (wrt) for water exported from a water region (wr); sums to unity over p and wrt
$l_{wrt,wr,p}$	loss rate per unit distance of water during transfer to destination (wrt) from a water region (wr), by transfer type (p) [/km]
$d_{wrt,wr,p}$	distance of water transfer to destination (wrt) from a water region (wr), by transfer type (p) [km]
$W^{imp}_{wr,p}$	water imported to a water region (wr) by type of transfer (p) [l/a]
$s^{tran}_{wr,wrf,p}$	share of transfer type (p) and source water region (wrf) for water imported to a water region (wr); sums to unity over p and wrf
$W^{put}_{b,tr,dis,imp\{s,t\}}$	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]

$W^{tr,dis,imp}_{\{s,t\}}$	water from treatment (*tr*), untreated discharge (*dis*), and imported by transfer (*imp*), by sector (*s*) and treatment type (*p*) [l/a]
$s^{put}_{tr,dis,imp,b}$	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^{take}_{b}	water obtained from water body types (*b*) [l/a]
$s^{take}_{b,s,ext}$	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^{des}_{s}	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]
$W^{\{in,out\}}_{y,\{b:gnd,riv,dam\}}$	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	evapouration loss from storage [l/a]
R^{dam}	release of water from storage into the river network [l/a]
$W^{riv}_{out,up}$	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]
$s^{trt}_{tr,tl}$	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]
$e^{exp}_{wr,wr}$	energy intensity of water transfer [J/l/km]
e_{tr}	energy intensity of water treatment service [J/l]

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