

Urban CALculator Model (UrbanCALM) - Consistent and Efficient Framework for Urban Water Balance Analysis and Reporting: 1. Description of the Model

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Abstract

Urban water managers confront complex tasks in planning and delivery of reliable water services for the growing urban centers and populations in the face of the impact of climatic variability. Increasing access to accurate and timely information on intake, usage and discharge by urban water systems can assist urban water managers in tackling the imbalance in water availability, supply and demand. The Bureau of Meteorology (under the Water Act 2007) has been mandated to improve water information this including developing Water Information products such as the annual National Water Account and Australian Water Resource Assessment Reports that are providing insights on urban water systems. To achieve this role, a nationally applicable and consistent framework is required, enabling to accommodate the diversity and varying complexity of the urban water systems. Such a framework needs to serve as a guiding tool for consistent data collection, interpretation, water balance analysis and presentation. This paper describes the Urban CALculator Model (UrbanCALM) developed by the Bureau to provide a consistent and efficient framework for urban water balancing and reporting on both simple and complex systems. It builds on the UrbanSAT (Urban System Analysis Tool) structured data capture and innovative framework. This framework is applicable to any urban water system nationally and internationally. The testing and application of UrbanCALM is presented in a companion paper.

Keywords: UrbanCALM, Urban Calculator Model, system analysis, urban water balance framework, urban water systems

1. INTRODUCTION

Globally, population living in the urban environment is greater than that in the rural environment. This has been the case since the beginning of the 21st century (Wong & Brown, 2009). The world's population residing in urban areas increased from 30% in 1950 to 54% in 2014, and is expected to reach 66% by 2050 (UN-DESAPD, 2014). Urban water managers are facing major challenges in the process of planning, development and delivery of water services resulted from growing populations and urban sprawl. There is an increasing demand for efficient and secure water services including water supply, wastewater and stormwater management. Need to address impacts of climatic variability and the associated risks including floods, and environmental degradation in growing urban environments further exacerbate the process of finding sustainable solutions to the task in hand.

Conventional urban water management practices aimed to meet water supply-demands while conveying wastewater and stormwater away from urban settings (Makropoulos *et al*, 2008). In responding to the challenges faced, urban water professionals have focused on transitioning to more water-sensitive and sustainable urban water management (Brown *et al*, 2008). Consequently, there has been an increased recognition and adoption of strategies for conserving limited water resources that need be shared among multiple-users in a region, which in many situations, have become susceptible under the climatic variability. To help alleviate pressures on the limited water resources available for urban supplies, urban water managers have turned to climate resilient water sources (e.g. desalinated water), and alternative urban water sources including rainwater. Options for reducing wastewater and stormwater volumes and increasing reuse have been adopted. These measures have enabled utilization of alternative urban water sources for appropriate purposes prior to their safe return to the environment, at the same time, reducing risks in urban areas.

Consequently, 'urban water systems' (water systems serving population centres) have become increasingly complex, having to encapsulate numerous 'urban water pathways' associated with water supply services, wastewater and stormwater collection, treatment, reuse and disposal. Several studies

highlighted the process taking place in many cities around the world transforming urban water systems to be more water sensitive and climate resilient, and supported development of useful strategies e.g. Brown *et al* (2009), Duong *et al* (2011). In Australia, where there has been a growing urgency on transitioning to more water-sensitive cities (Wong & Brown, 2009). Several studies focused on providing insights and facilitating different aspects of this transformation process e.g. Brown *et al* (2009), Mitchell *et al* (2001 & 2007), Snowdon *et al* (2011) and Burn *et al* (2012). However, a key requirement that can assist urban water managers to address the challenges faced and enable the necessary transformation process is increased access to ‘accurate’ and ‘timely’ information’ on urban water systems. Due to the increasing complexity of the systems serving today’s urban centers, provision of such information in a consistent manner has become a major task and in needs.

The Australian Bureau of Meteorology (the Bureau) has responded to this information need by developing reporting products to meet its legislated role (under the Water Act 2007) in providing an annual National Water Account (NWA) and regular Australian Water Resource Assessment Reports (e.g. BoM, 2014a & 2012b). Both products provide insights into urban water systems. In preparing these reporting products, a consistent framework is required. The Bureau collects data on water intake, supply, and disposal by the urban water systems from many data providers. Usually there are inconsistencies in these data and differences between water systems. A framework that can improve efficiency and consistency of data collection, processing, and streamline the reporting process is needed, and can strengthen the Bureau’s capacity to deliver high quality Water Information (WI) products. Such a framework could also be useful to any other organization providing similar functions. It is, however, a challenge to identify a generic urban water balance framework that is transferrable and nationally applicable for representing, analyzing and reporting on urban water systems in a consistent and timely manner at different spatial scales. This paper describes the Urban CALculator Model (UrbanCALM) developed by the Bureau to provide a consistent and efficient framework for urban water balancing and reporting on both simple and complex systems.

1.1. Urban Water Balance Approach and Challenge

The water balance approach, which is the principle of mass conservation (McPherson, 1973), has been traditionally employed to account for the movement of water through the hydrological cycle over a selected time interval at different spatial scales (Grimmond *et al*, 1986). In the unique and complex system in the urban environment (Essery, 1995), the ‘natural’ water cycle occurs impacted by urbanization and linked to the ‘urban’ (man-made) water system. The water balance approach can be used to investigate exchanges of flow between the system’s elements along each of these pathways i.e. ‘natural’ and ‘urban’ pathways that form the ‘total water cycle’. Also it allows analysis of exchanges of flow via the links between elements of the ‘urban’ pathway (urban water system) and elements of the ‘natural’ pathway.

Significance of the urban water balance has been recognized since several decades ago. For example, McPherson (1973) highlighted the need for metropolitan water balance inventories. Despite this early recognition and growing urgency to plan more water-sensitive cities in recent years (Wong & Brown, 2009), water balance of most cities is not well known (Kenway *et al*, 2011). Having compared elements of the urban water balance at city scale reported in various articles, Kenway *et al* (2011) attributed the paucity of fully-populated city-scale mass balance examples to the complexity of the urban water cycle.

In general, due to the associated multiple water flow pathways, evaluation of water balance within the ‘water sensitive’ (and more climate resilient) urban landscape is more complex than such evaluations in other i.e. natural, rural and conventional urban landscapes (Figure 1). Nonetheless, the water balance approach has been utilized to investigate urban water systems or to assist in the development of sustainable urban water management options e.g. Grimmond *et al* (1986), Essery (1995), Hellström *et al* (2000), Snowdon, *et al* (2011), Núñez *et al* (2010), Maheepala *et al* (2005), Mitchell *et al* (2001), Mitchell *et al* (2003), Duong *et al* (2011), and Binder *et al* (1997).

A nationally applicable urban water balance framework, however, needs to have several attributes and capabilities enabling to serve multiple purposes. These include: capacity to accommodate diversity and varying complexity of the urban water systems; capability to provide a guiding tool to streamline data collection and interpretation; ability to facilitate consistent and accurate water balance evaluations of water systems at different scales (within a region as well as across regions); and suitability to provide a

platform for transparent and defensible reporting. This paper describes the Urban CALculator Model (UrbanCALM) development that provides a consistent and efficient water balance evaluation framework. The Testing and application of the model or framework is presented in the second part of this publication.

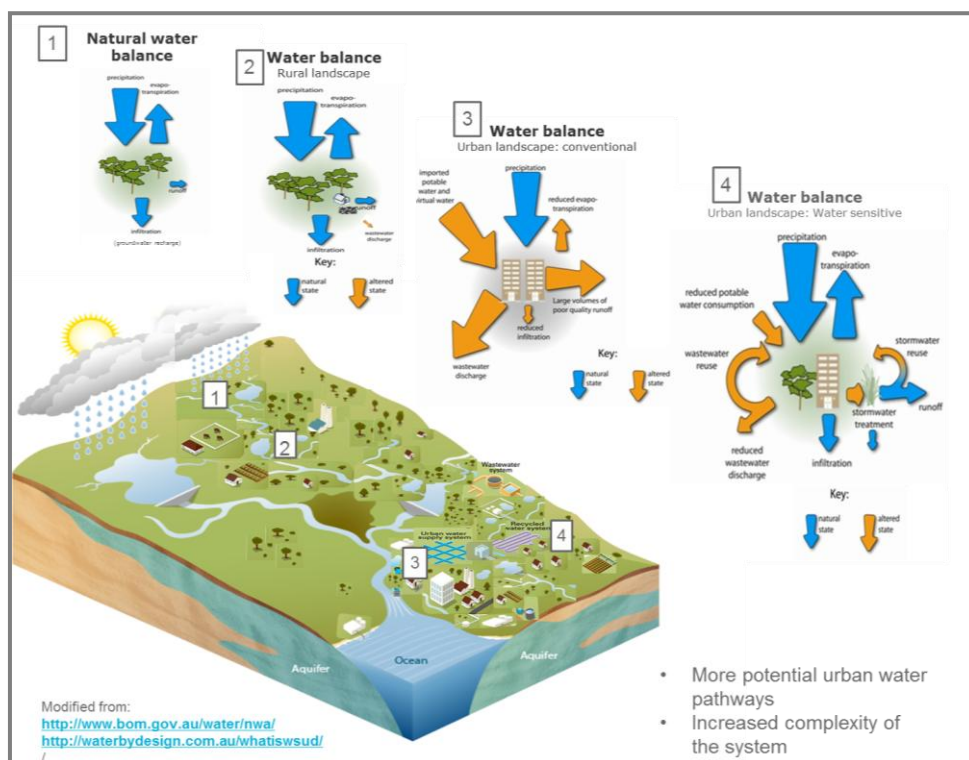


Figure 1: Increasing complexity of the water balance through different landscapes

2. MODEL CONCEPTUALIZATION

UrbanCALM builds on the structured data capture and innovative framework of UrbanSAT - Urban System Analysis Tool (Elmahdi *et al*, 2011). The UrbanSAT's concept clarifies sharing of water resources for urban purposes among other users in a region. It was developed to capture and analyze data for providing a greater transparency of the flow through urban water systems (Figure 2), as part of reporting on six major Australian urban regions / cities in the NWA 2010 (BoM, 2011). UrbanCALM inherits the strengths and limitations associated with the UrbanSAT concept and its implementation, as elaborated in the following sections.

The UrbanSAT framework (Elmahdi *et al*, 2011) incorporates information via the whole of system basis and system analysis, clarifying water intake and transfers, supply for use, wastewater collection, treatment, disposal and reuse (Figure 2), which are represented by UrbanSAT (data) items. The UrbanSAT concept can be applied to a selected area where the metered or estimated data are available to populate UrbanSAT items relevant to the urban water system. It can be applied to the service area of a water authority, which may be a subarea within the 'larger region' defined by: (a) hydrological boundary, or (b) the total area of a city. UrbanSAT enables a unique view of flow through the urban waters system and clarifies its linkage with the regional groundwater and surface water (e.g. reservoirs and rivers) systems and landscape (Figure 2).

The UrbanSAT framework can be implemented for clarifying flow through the 'urban water cycle elements' (which represent the 'urban water system') and their interaction with surface water, groundwater and landscape within a given time interval. The 'starting points' of UrbanSAT (and hence UrbanCALM) application in a given situation are the points of intake of water from urban water sources or transfers (or imports if across the region boundary) of different water types into urban water system. The outflows from the urban water system e.g. transfer outs (or exports if across the region boundary), supply for use, disposals, discharge and losses of different water types represent 'ending

wastewater and recycled water subsystems) and their interaction with the regional system. As illustrated by Figure 3, water supply system represents the intake of several types of urban water sources, including surface water, groundwater and desalinated water for water supply in evaluating its water balance. Due to the limited access to the required information and limited potential benefits users at the scales involved, intake and use of stormwater, and individual water intake and use (i.e. water not provided via the centralized services or managed by the water authorities) are not included in the UrbanSAT implementation for providing input to the NWA. Intake of such water sources and the relevant usage can be suitably incorporated via appropriate implementation of UrbanSAT within UrbanCALM for other WI products at appropriate spatial and temporal scales where the relevant data can be captured and the user needs can be addressed. However, even in the current implementation of UrbanSAT, the wastewater system captures discharges to sewer following the use of such water sources and the pathways afterwards in its water balance evaluations.

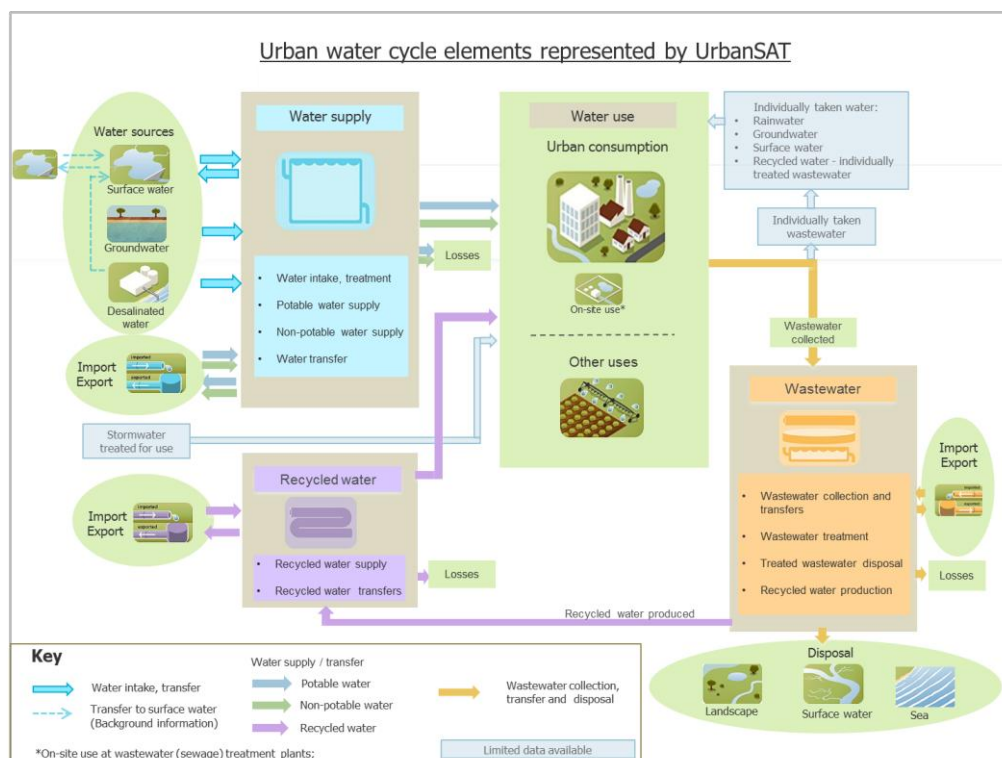


Figure 3: Implementation of UrbanSAT for providing input to the National Water Account

3. DESCRIPTION OF THE URBANCALM FRAMEWORK

The UrbanCALM concept was developed with the aimed of providing a consistent and efficient urban water balancing framework for both simple and complex systems and is implemented via several modules (Figure 4). It utilizes the 'urban water pathways analysis' that supports water balance assessments to untangle urban water systems with varying complexity. Underpinned by the UrbanSAT structured data capture framework, UrbanCALM was designed to facilitate consistent data interpretations and analysis, and to automate outputs enabling insights into urban water systems for their integration into WI reporting products. The representation of the urban water system in UrbanCALM is in line with the implementation of UrbanSAT to provide input to a particular WI reporting product. Figure 5 illustrates the conceptual representation of the urban water system at the water authority (utility) scale in UrbanCALM for providing input to the NWA.

3.1. UrbanCALM Modules

UrbanCALM comprises of several modules (Figure 4) implemented via Microsoft Excel with links to allow passage of information from the 'raw data' stage through the 'analysis' stage to 'output'. The

‘Input’ module comprised of UrbanSAT along with a suite of supporting items clarifying the components contributing to different types of input data items, and schematics illustrating relevant flows identified from the ‘analysis of urban water pathways’ that are represented by the data items.

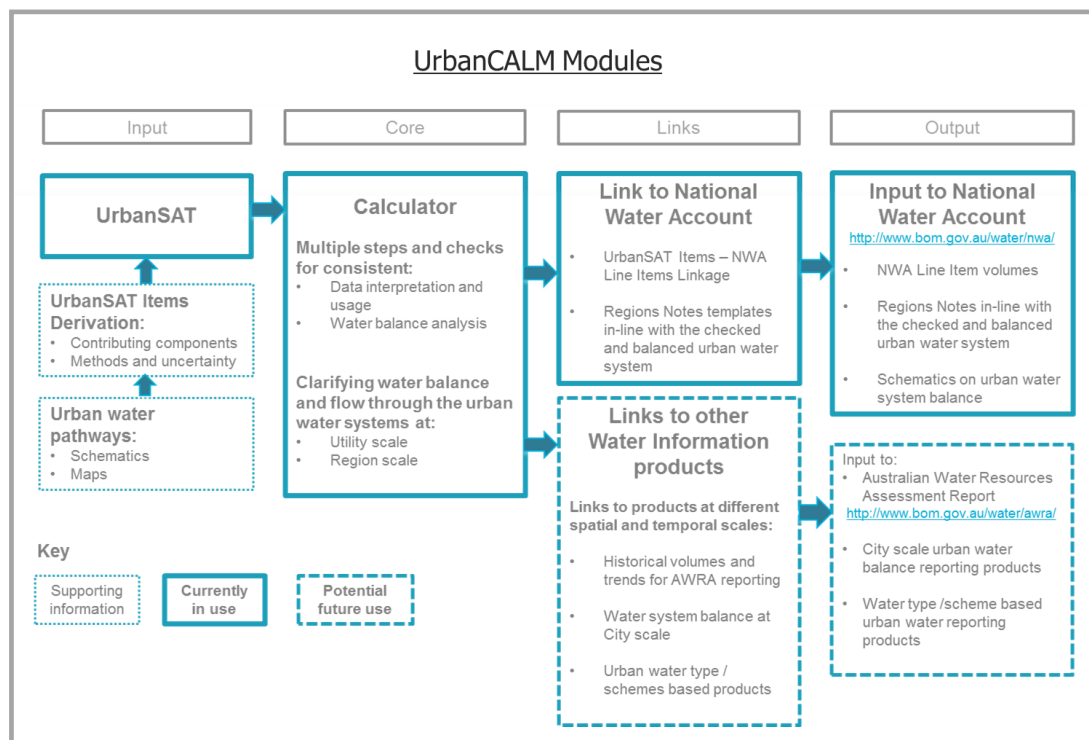


Figure 4: UrbanCALM modules

The core module of UrbanCALM is the ‘Calculator’ which aids accurate representation of inflow and outflow components relevant to each subsystem of the urban water system: (1) water supply system, (2) wastewater system and (3) recycled water system. Based on the principle of mass balance, the Calculator performs consistent water balance evaluations relevant to each subsystem within a given time interval. The aim is to follow the flow through each subsystem due to the volumes taken in during the time interval concerned taking into consideration relevant, inflows to the system (intake, imports or transfers in) and outflows (exports or transfers out, supply for use, discharge, disposal and losses). This approach doesn’t require volumes relevant to the functioning of each subsystem to be specified explicitly if a suitable time step is chosen e.g. an annual cycle. However, if there are known changes to the operational volumes within the time interval chosen, the mass balance principle can be suitably adopted to account for those. For example, where any part of the volume of water taken into a subsystem is allocated to increases an operational storage (e.g. due to a pipeline extension, or stored specifically for a future use), such volumes can be treated as ‘equivalent’ outflows during the time interval concerned. Similarly, taking of excess volumes from operational storages can be treated as ‘equivalent’ inflows. Increased intakes from sources such as surface water storages or bore fields (e.g. in drought years) are accounted via the inflow of water to the urban water supply system from such sources, which are part of the input data collected for the analysis. However, water in storage represented by such sources are not required to be part of the input data, as those storages are beyond the starting point (water intake) of the UrbanCALM application.

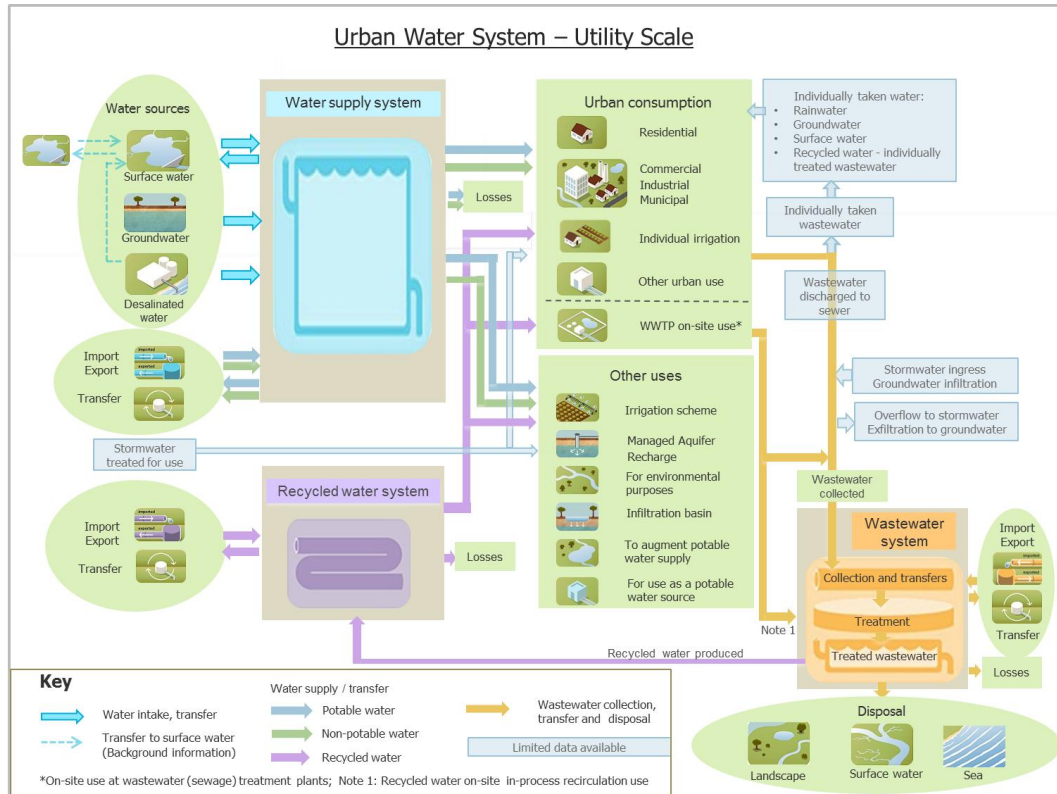


Figure 5: Conceptual representation of the urban water system at utility scale in UrbanCALM

The Calculator is equipped with steps and checks to facilitate consistent data interpretations and water balance analysis. It enables detection of missing water balance components and misinterpretation of water flow pathways by comparing 'Total inflow' and the 'Total outflow' relevant to each subsystem, and at critical points within a subsystem. For each subsystem, percentage 'system error' or the 'unaccounted difference' is calculated based on the total inflow, as:

$$\text{System error} = (\text{Total inflow} - \text{Total outflow}) \times 100 / \text{Total inflow} \quad (1)$$

The 'Links' module (Figure 4) is represented by the features included in UrbanCALM that enables conversion of the checked and balanced water balance components to suitable formats for incorporation into a particular Bureau WI reporting product. In the process of providing input to the NWA, links enable derivation of the items listed in the 'Output' module (Figure 4) including 'Line Item' volumes and schematics summarizing the water balance of each subsystem of the urban water system. These items in turn enable preparation of 'Line Item Notes' which clarify the derivation of Line Item volumes presented.

In general, the UrbanCALM process enables derivation of outputs in different formats as required for different reporting products including Table, Figure or Graph formats (Figure 6). The results can be displayed via templates as appropriate for inclusion in the WI products including the National Water Account, Australian Water Resources Assessment report, and city based urban water reporting.

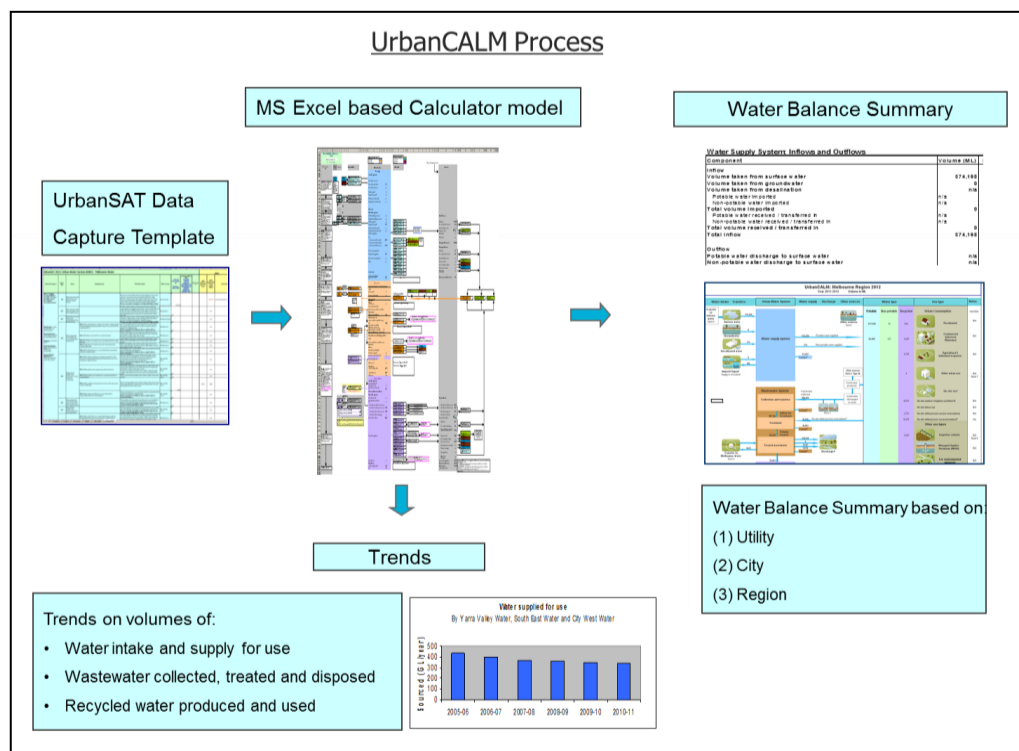


Figure 6: The UrbanCALM process: from raw data through analysis to output

3.2. Deriving Insights on Urban Water Systems

The water balance evaluated through the UrbanCALM process can be used to derive various insights for providing improved transparency of water flow through urban water systems including:

- Water balance summary indicating relevant volumes of total inflow, total outflow, system error (see equation 1) for each of the subsystems i.e. urban water system, wastewater system and recycled water systems, at (a) water utility, and (b) regional scales;
- Comparison of water taken and imported based on water types: e.g. surface water, groundwater, desalinated water or recycled water (a) within a region based on utility based systems, and (b) across regions i.e. national scale based on regional systems;
- Comparison of water balance components in a given year e.g. (1) supply of potable, non-potable or recycled water for residential use (volumes or percentage based on total water supplied for use); (2) wastewater volumes collected, treated reused and disposed to rivers, sea or landscape, (a) within a region based on utility based systems, and (b) national scale based on regional systems;
- Based on several years of results e.g. as in B and C, comparisons of trends in water balance components (a) within a region based on utility based systems, and (b) national scale based on regional systems.

4. SUMMARY AND CONCLUSIONS

Urban water managers face complex challenges in planning, development and delivery of robust and secure water services (water supply, wastewater and stormwater management). These include the need to supply and service growing populations and urban areas and manage the impacts of climatic variability. Increased access to accurate and timely information on intake, usage and disposal by urban water systems can assist urban water managers in addressing the challenges faced.

This paper described the Urban Calculator Model (UrbanCALM) developed by the Bureau to provide a consistent and efficient framework for urban water balancing and reporting on both simple and complex systems. It was developed based on the UrbanSAT framework, and facilitates stepwise and systematic evaluation of the water balance within each component of the urban water system (water supply system, wastewater system and recycled water system). UrbanCALM includes multiple checks

to detect anomalies in the usage of urban water data. Such features enable it to serve as a guiding and evaluation tool for consistent data collection and accurate interpretation, and to facilitate consistent water balance analysis at the water utility scale within a region and across regions at the national scale. UrbanCALM automates outputs on water balance summaries and helps derivation of insights for providing greater transparency of flow through urban water systems. UrbanCALM is applicable to any urban water system nationally and internationally. The testing and application of the UrbanCALM framework is presented in a companion paper.

5. ACKNOWLEDGEMENTS

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Dr Chandrika Jayatilaka received her BSc (Eng.) degree from the University of Moratuwa, Sri Lanka, and her PhD specializing in hydrological processes from the University of Waterloo, Canada. Chandrika has contributed to a wide range of hydrological studies and research projects, the results of which are published in a number of journal articles and conference papers. She has developed hydrological models for representing surface water balance, groundwater systems and for simulating near-stream flow dynamics. Chandrika has also contributed to projects dealing with urban water systems and alternative urban water sources. As a Senior Hydrologist with the Water Resources Assessment Section, Environment & Research Division of the Australian Bureau of Meteorology, Chandrika worked on the development of tools to capture information on urban water systems, and facilitate water balance analysis and reporting on urban systems serving Australia's major population centres.

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