Chapter 2
Integrated Water Cycle Modelling of the Urban/Peri-urban Continuum

Hector Malano, Meenakshi Arora and K. Rathnayaka

Abstract The world is undergoing an intensive process of urbanisation. In 2008, for the first time in history, over half of the world's population was living in urban and peri-urban areas. It is estimated that this number will increase to 5 billion by 2030 with most of this growth occurring on the edges of mega-cities. Smaller cities are also undergoing large transformations. Urbanisation can bring opportunities for people to improve their standard of living and access to education and other services but it can also bring and concentrate poverty in developing countries where most of this urban growth is occurring. Increased urbanisation presents planners and policy makers with many challenges, foremost among them, competition for land and water resources with other sectors such as agriculture. Critical to our capacity to develop a sound urban transformation policy is our ability to integrate science to support the formulation of sustainable planning strategies. Increasing competition for water in many regions of the world provides an impetus for increasing use of water saving and replacement techniques, such as water reuse and recycling and urban runoff harvest. This new paradigm requires an improved capability for integrated modelling approaches to analyse the whole-of-water-cycle. Such an approach involves the integration of the various sub-systems—Catchment (surface-groundwater), water supply systems, wastewater, water allocation, internal recycling, decentralised treatment and storm water harvesting. Adding to this system complexity is the need to consider water quality as a constraining factor when using a fit-for-purpose approach to integrated urban water management (IUWM). This paper focuses on the challenges and opportunities involved in modelling the urban/peri-urban water cycle for planning of urban and peri-urban systems, including spatial and temporal scale and integration of hydrologic, water allocation with differential water quality across catchment and political divisions. Case studies are used to illustrate the use of integrated water modelling to inform a scenario planning approach to integrated water resource

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management in an urban/peri-urban context. In this analysis, two main constraints to effective modelling are identified—Lack of model integration and lack of data in the appropriate time and spatial scale often stemming from the lack of a robust data monitoring program of the entire water cycle. A framework for integration of water system modelling with economic modelling is presented.

Keywords Urban water cycle · Modelling · Water supply · Water demand · Decentralized systems

2.1 Introduction

The world is undergoing an intensive process of urbanisation. In 2008, for the first time in history, over half of the world's population was living in urban and peri-urban areas. It's estimated that this number will increase to 5 billion by 2030 with most of this growth occurring on the edges of mega-cities, although smaller cities are also undergoing large transformations (Worldwatch Institute 2008).

Urbanisation can bring opportunities for people to improve their standard of living and access to education and other services but it can also bring and concentrate poverty in developing countries where most of this urban growth is occurring. Increased urbanisation presents planners and policy makers with many challenges, foremost among them, competition for land and water resources with other sectors, such as agriculture.

Achieving these goals in a sustainable manner represents an additional challenge as new economic activities in the urban environment face increasing pressure to reduce their carbon emissions. Management of the water cycle in its entirety must be carried out in a way that minimises resource demand, Green House Gas (GHG) emissions and other environmental impacts.

2.2 Urban/Peri-urban Land Use Continuum

Peri-urbanisation is a complex process that occurs across a range of metropolitan and non-metropolitan landscape settings which often straddle a continuum of land uses ranging from urban residential centres to agricultural land. Chow et al. (2008) identifies several combinations of land uses that include peri-urbanisation associated with urban metropolitan centres, regional centres and discrete urban centres in rural and regional areas. Figure 2.1 provides a pictorial example of these scenarios for the Melbourne Metropolitan area and surrounding green wedges (Buxton and Goodman, 2002).

Fig. 2.1 Melbourne metropolitan area and surrounding peri-urban areas. *Source* Buxton and Goodman 2002

Peri-urban areas undergo a continuous and dynamic process of land use change as a result of economic and demographic forces including changes in the agriculture and cropping profile, conversion of agricultural land into residential, commercial or industrial development. From a hydrological point of view, these changes in land use have a direct impact on the water cycle, in particular, the behaviour of runoff generation and the pattern of water demand.

2.3 Urban/Peri-urban Water Cycle

Multiple and changing land uses in peri-urban areas lead to continuous changes in the hydrologic and water supply-demand configuration of the water cycle. The consideration of alternative planning and development scenarios demands modelling capability that describes these critical processes involved.

Modelling of the water cycle must be designed with a view to assessing the various responses to the changing landscape and the resulting water security and sustainability performance. There is ample literature related to the use of environmental sustainability indicators (ESI) for urban water systems (Lundin and Morrison 2002). It is important to note that there is a proliferation of articles proposing different ESIs but not many refer to the need to develop a set of criteria to select these ESIs. An approach increasingly used by industry is based on life cycle assessment (LCA). When applied to the urban water cycle, this approach entails defining the geographical boundaries of the system (upstream and downstream cut offs). The LCA of an urban system begins with the diversion of water from surface or groundwater and ends with the discharge of treated/untreated storm water and wastewater, and must include a time series analysis that reflects the life of the physical infrastructure. These processes are linked to other resources, such as energy and other linked processes such as GHG emissions resulting from moving water and wastewater, incineration of sewage sludge and disposal as waste.

Various authors have described the key elements of the urban/peri-urban water cycle to include the following:

- Catchment (surface/groundwater)
- Water Supply system
- Sewerage and wastewater treatment systems
- Water sharing and allocation (matching multiple supplies and demands)
- Receiving water system.

At a sub-system level, complexity may vary to include internal processes and interactions between subsystems which could include internal recycling processes such as:

- Use of water tanks
- Decentralised water treatment
- Storm water harvesting.

An increase in number of subsystems, and in particular the degree of interaction between these subsystems, will determine the complexity of the system.

2.4 Water Cycle Modelling

Systems models are designed to represent an abstraction of the processes involved in the systems and sub-systems outlined above. Often, modellers have a proclivity to isolate individual systems to reduce complexity. Water cycle modelling can be described by a hierarchy of sub-systems that encompass the whole-of-water cycle through a progressive disaggregation of the various subsystems (Khan et al. 2008; Malano 2010).

Importantly, it is necessary to recognise the many interactions that occur across the individual subsystems boundaries that are represented in the Integrated Urban Water Management modelling framework.

2.5 Resource Assessment and Allocation

Surface and groundwater modelling is used to determine changes in water generation arising from alternative and changing land uses in the catchment. Land use changes are the result of the dynamic changes resulting from the continuous evolution of urbanisation of peri-urban areas, usually conversion of rural land to urban use and consequent alteration of pervious and impervious surface areas.

The main objective of a hydrologic study is to assess the source and quantity and quality of available water resources. This is best accomplished through rainfall/runoff modelling that is capable of representing a mosaic of land uses in the catchment, usually by applying a distributed or semi-distributed rainfall/runoff modelling approach. In order to properly model a hydrologic system, consideration should not only be given to surface water, but also to groundwater, land use, soil type, existing land and water use practice, including any conservation measures, nutrient cycles, as well as historical data concerning rainfall patterns.

Figure 2.2 depicts the land use in the South Creek catchment, Western Sydney, a typical peri-urban catchment with multiple forms of land use. South Creek catchment covers approximately 620 km^2 and contains portions of eight LGAs, five of these political entities account for a significant proportion of the catchment. In addition, all five LGAs extend well beyond the boundaries of the catchment. In this study a semi-distributed model (BTOPMC) was employed to describe the land use configuration of the catchment. It is a physically-based distributed hydrological model based on block-wise use of TOPMODEL, with the Muskingum-Cunge flow routing method that has been used for simulating runoff in different sized watersheds. Nawarathna and Kazama (2006) extended this model by introducing distributed parameters and applying it to a part of the Mekong River basin. In a semi-distributed model, like BTOPMC, identified processes are simulated in daily time steps. This provides the required detail for the spatial and temporal modelling of water allocation.

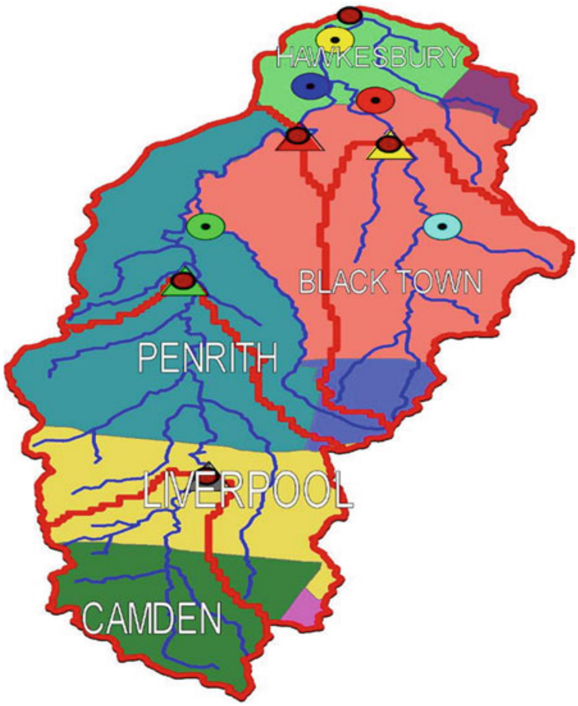

Fig. 2.2 South Creek catchment

The existing supply sources in the South Creek catchment include potable water, surface water, and groundwater. It is envisaged, however, that future increases in water demand will require a comprehensive portfolio of alternative water sources, including storm water harvesting and effluent recycling which will be used on a fit-for-purpose basis to meet multiple demands, such as domestic indoor use, domestic outdoor use, commercial/indoor use, irrigation and environmental flows (Fig. 2.3). The schematic of the water allocation and substitution model is shown in Fig. 2.4. A salient feature of the South Creek modelling system is the discrepancy between the hydrologic landscape and the political divisions represented by the Local Government Areas (LGAs).

A modelling framework consisting of the BTOPMC model coupled with the Resource Allocation Model (REALM) (Perera et al. 2005) was applied to analyse a set of scenarios formulated by a partnership between researchers, stakeholders and decision makers. These scenarios reflect a combination of land use changes—natural growth and concentrated growth centres—and use of storm water harvesting, effluent reuse to supplement environmental flows and improved on-farm irrigation efficiency.

Following the assessment of available resources, we must focus our attention on the allocation of resources to meet various water end-use demands. Water allocation and substitution refers to the approach used to match water resources quantity and quality with alternative demands subject to water quality constraints.

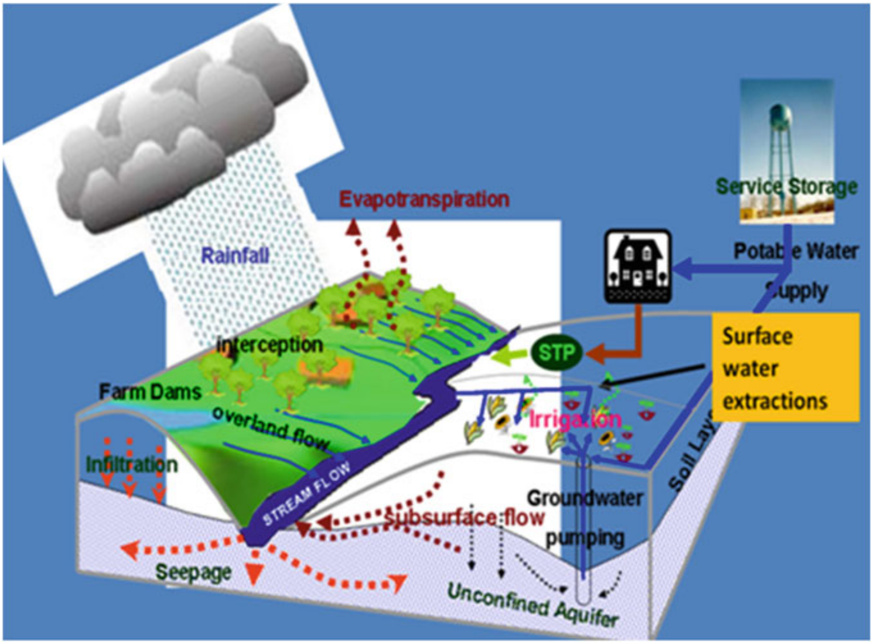

Fig. 2.3 The South Creek catchment water system. *Source* Singh et al. 2009a, b

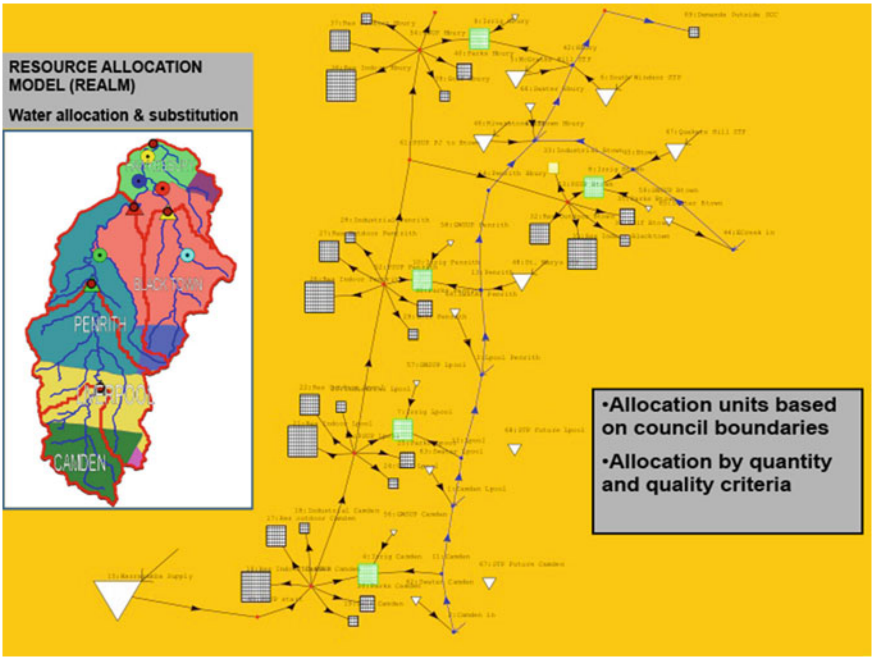

Fig. 2.4 Schematics of water allocation-substitution model. *Source* Davidson et al. 2013

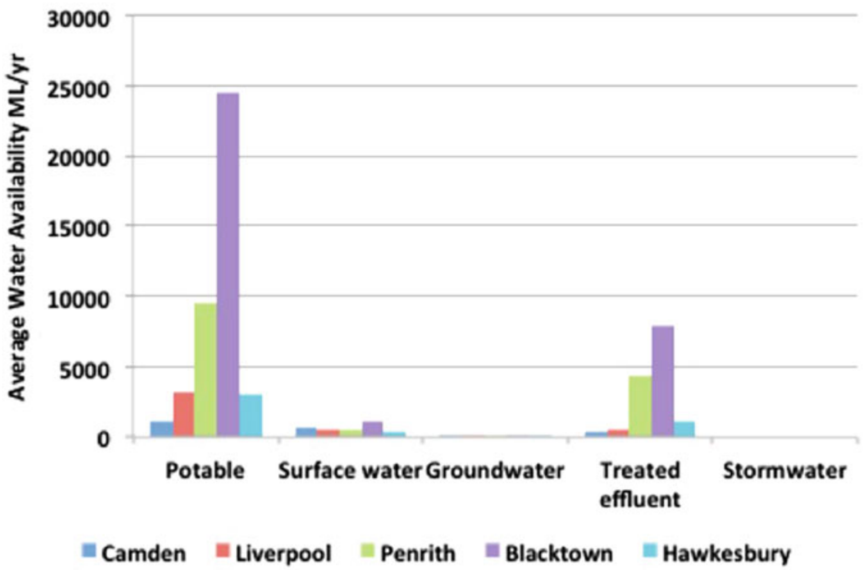

Fig. 2.5 Allocation substitution results for each LGA in South Creek, Western Sydney. *Source* Singh et al. 2009a, b

Usually, a fit-for-purpose criterion is used to allocate the resource. This objective is usually achieved through the application of the REALM water allocation model (Perera et al. 2005) which can accommodate various priorities of allocation and quality constraints for the alternative pathways between water availability and water demand.

Figures 2.3 and 2.4 provide a schematic representation of the water resource system in South Creek catchment, Western Sydney. The supply sources in the South Creek catchment include potable water, surface water and groundwater, treated effluent and treated storm water. Water demand was segregated into residential indoor and outdoor, industrial, primary production, open space irrigation and environmental flow. Demand in each of the LGAs was split between four categories based on use and anticipated differing value of resources—residential, industrial and commercial, agriculture and recreation.

Figure 2.5 presents a sample of modelling results for the effluent reuse option. The allocation-substitution modelling shows the average water available to each LGA segregated by water class. These are average water allocation amounts for the period 2008–2030, assuming a medium impact of climate change.

The system's security of supply is of critical importance to planners and decision makers. Security of supply is represented by the combination quantity of water available at a specified probability of assurance. The derivation of this metric requires a sufficiently long time series of data input and modelling outputs. A more detailed discussion about security of supply can be found in George et al. (2011).

2.6 Urban/Peri-urban Subsystems Modelling

An urban water supply and wastewater system consists of a number of individual but connected subsystems. Modelling of each individual subsystem is often necessary to analyse the individual subsystem's performance and the interactions with and impacts on other subsystems and on various components of the water cycle. In the following, we discuss the main sub-systems that are present in the urban/peri-urban water cycle and key modelling considerations related to the main subsystems.

Water supply subsystem: This may include a number of options and configurations such as centralised and decentralised systems, and various forms of alternative water sources including stormwater, rain water tanks and recycled effluent. Traditionally, centralised systems have been the predominant type of infrastructure for water supply and wastewater collection systems combined with a single-use of water modality. But high population growth in urban and peri-urban areas, intensive agricultural development, urbanisation and industrial growth are all leading to an increased demand for water and are forcing many cities to reconsider their present water management strategies and practices. Many countries around the globe are now looking for alternative water supply options to ensure future water security via a mix of centralised and decentralised systems.

The IUWM approach to water management is increasingly embedded in the planning process of many urban and peri-urban areas to provide sustainable water services to communities and to the environment (Maheepala et al. 2010). This approach seeks to utilise diverse water sources, including grey water, roof water, recycled water, stormwater, surface water, groundwater and desalinated water at different spatial scales on a fit-for-purpose basis. Some of these sources, such as recycled water, can be available at larger spatial scales, such as whole-of-city scale. Other alternative supplies, such as roof water, grey water and stormwater, can be available for individual households. In addition to considerations of spatial, temporal scales are important for both availability and demand, since these vary at the sub-daily scale. Thus, these are important considerations when developing a modelling strategy for optimal use of the multiple sources of water to satisfy multiple fit-for-purposes which must be based on a detailed understanding of the multiple end-uses at different spatial scales (household, precinct, suburb and city scales) and temporal scales (sub-daily to annual scale).

Water demand subsystem: Water demand and its various components is one of the main forcings of the water supply subsystem. There are a number of end-use components that determine the overall water demand, including indoor uses (cooking, washing, bathroom) and outdoor use (gardening, car washing). These individual components of demand are often determined from household surveys or actual meter readings and then extrapolated at different spatial scales (precinct, development, city) and various economic sectors (residential, commercial, amenities). This is a deterministic approach which does not account for the behavioural drivers that affect the pattern of demand. Typically, this type of demand

Table 2.1 Water supply and demand drivers in urban and peri-urban areas

	Residential	Non residential	Open spaces	Roads and pavements
Building typology	Single houses Attached houses Apartments	Office buildings Schools/Colleges Industrial/commercial	Parks Golf courses	Roads
Water supply sources	Imported water Rainwater Stormwater Grey Water Sewer mining Groundwater	Imported water Rainwater Stormwater Grey Water Sewer mining Groundwater	Rainwater Stormwater	Rainwater Stormwater
End use water demand	Kitchen Toilet Showers Dishwasher Laundry Taps Leaks Heating/Cooling Irrigation Evapotranspiration	Kitchen Toilet Showers Dishwasher Laundry Taps Leaks Heating/Cooling Irrigation Evapotranspiration	Leaks Irrigation Evapotranspiration	Evapotranspiration

assessment is conducted on a monthly or annual time scale and is used for aggregate modelling at the initial feasibility assessment stage for a new urban development. These methods of water demand forecasting are dependent on none or few variables and produce water demand outputs that have been used in early simple econometric and time series models.

With the increasing importance of IUWM, modelling must take a more holistic approach to characterising water demand. Consequently, the role of water demand forecasting and simulation has also changed substantially. The degree of complexity of urban water systems modelling arises from the need to incorporate better predictive capability of the constant changes due to demographics, urban renewal, technology take-up rates and changing water policies (Mitchell et al. 2001).

Identifying how urban residential water demand varies over space and time and its underlying factors is considered critical to our ability to extrapolate future predictions. In a recent study, Roberts (2005) and Willis et al. (2009) identified the significance of spatial variability of urban residential water demand at household scale by conducting an intensive data collection of end-use water use.

Decentralised water supply systems are beginning to play an increasing role in the provision of urban water. There is limited research to date focusing on predicting water demand of differential quality and constrained uses to enable planning of this type of system. This is a critical limitation in the current ability to represent these processes in IUWM models.

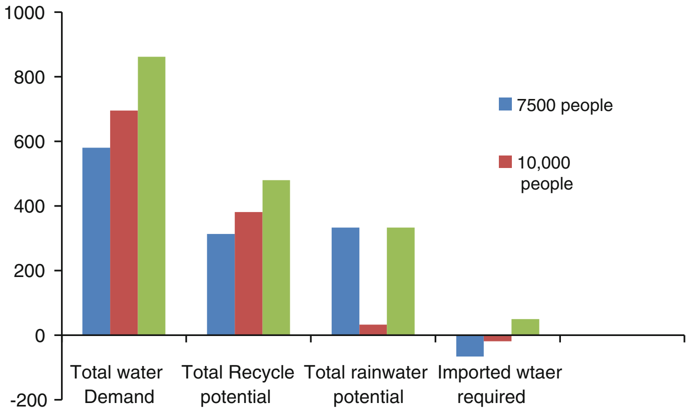

Fig. 2.6 Water demand and supply options for three different density scenarios for a new development. *Source* Arora et al 2013

A more sophisticated approach named 'end-use modelling' can be used to elucidate the complex interactions between forcing variables that drive end-use demand dynamics at different spatial scales. This modelling approach allows the representation of all objects and typologies, such as residential (detached houses, multi dwelling and apartments), non-residential (commercial and industrial), open spaces (parks, golf courses etc.) and roads, that populate the urban landscape. A summary of water supply and demand drivers is shown in Table 2.1 which describes the various sources of water at various scales and water demand at end-use level. End-use water demand depends on various building attributes like occupancy, land size (area), roof area, paved area and unpaved (green) area.

Modelling of water availability must simulate the water available from various sources like roof rain water, stormwater, grey water reuse, wastewater recycling, groundwater and desalination. This modelling approach aims to model availability at different time scales ranging from diurnal to annual time steps and spatial scales ranging from individual dwellings to whole precincts. Rathnayaka et al. (2011) presents a comprehensive review of the existing modelling capability to describe end-use demand and the current gaps and opportunities that still need to be addressed in this domain. Their review found that the existing end-use models have limited capacity to describe water demand at various spatial and temporal scales. This is due to these models describing water demand based on average values and lack of capacity to describe the complex relationships between variables and the limited availability of data to validate these relationships.

Figure 2.6 presents an example of the total water demand for a new residential development site in metropolitan Melbourne with three different scenarios of development density. There are three main sources of water supply available locally in addition to imported water—roof rain water, storm water and recycled wastewater—Water demand increases with increasing density which in turns leads to an increase in the amount of recycled water available on the site. It is important to note that roof rain water and storm water available on site is finite as these are determined by climate. In this case study, the population density must be maintained below the maximum capacity of 10,000 residents to achieve self-sufficiency of water provision and avoid resorting to additional freshwater water imports. The current site will provide water for a population of up to 10,000 residents in an average rainfall year, but it will require additional imported water for a population density of 13,000 residents.

Wastewater treatment subsystem: This may include several options such as classical centralised systems and increasingly the use of decentralised treatment systems. Wastewater systems may also incorporate downstream recycling of wastewater and waste into various kinds of agricultural products such as fertilisers and energy generation. Health and risk management are the most important factors in decentralised wastewater treatment systems. The performance of the wastewater system can be affected by the physical configuration of the system and unintended connections with the urban runoff system which may significantly increase the waste water stream.

Decentralised wastewater treatment systems can be used to reduce the need for new water supply to satisfy an increasing demand. The introduction of decentralised systems, such as sewer mining, however, can create changes in the composition and concentration of wastewater which may compromise the operation of the receiving centralised system.

A key aspect that must be considered in integrating wastewater into the water cycle modelling is the description of all water and solutes fluxes across the entire wastewater system. This is of particular importance if wastewater disposal becomes an important consideration in determining impacts on the receiving water subsystem and meeting effluent quality standards.

A similar degree of detail required to model water supply processes that involve multiple fit-for-purpose sources is needed for wastewater, as there is a direct relationship between wastewater generation and water use. Identifying end-use water demands at multiple scales also enables the prediction of wastewater outputs with different quality levels at different scales. This understanding is particularly necessary to incorporate decentralised reuse of wastewater within an IUWM framework.

Receiving waters subsystem: In systems where there is an outfall to a receiving body of water, the impact on the quantity and quality of water is an important consideration. This refers to a broad range of physical, chemical and biological variables and is aimed at describing the cause-effect relationships and pollutants pathways from points of origin to removal. These are dynamic processes that require considering modelling time scales that vary from small time steps (fractions of a second) to describe for example the impact of a rainfall event on pollutant fluxes to much longer time steps to describe groundwater pollution processes.

Table 2.2 Modelling time scales, spatial scales and dimensionality in urban/peri-urban water cycle

Subsystem	Time scale	Spatial scale
Bulk assessment and allocation	Monthly to annual	Catchment Political division
Water supply subsystems	*End-use models*: seconds to daily *Feasibility studies*: monthly-annual average	*End-use models*: single to multiple dwellings *Feasibility studies*: aggregate-stratified clustering
Wastewater subsystems	*Dynamic models (quantity-quality sewer flow)*: fractions of seconds to hours for short term dynamic processes and continuous simulation	*Treatment plant*: whole of plant system
	Performance assessment: monthly to annual	*Sewer subsystem modelling*: individual sewer subsystem component *Drainage pollution loads*: catchment/sub-catchments
Receiving waters subsystem	*Surface water dynamic modelling*: seconds to hours *Groundwater*: daily to monthly	*Surface water bodies*: partial or whole water body *Groundwater*: partial or whole aquifer depending on objective and affected area

2.6.1 Integrated Modelling Challenges

There are a number of models available that are used to represent and describe individual subsystems (water supply, wastewater and receiving waters) that run largely independently with exogenous data transfer between models (Rathnayaka et al. 2011). The main constraint imposed by this approach is that data and model processing can only occur sequentially in the downstream direction, thus precluding feedback between subsystem models. Simultaneous processing will allow these feedbacks to be taken into consideration. Integration of all water quantity and quality modelling processes still remains a challenge, highlighting the need to harmonise the interfaces between models.

The two main obstacles that must be addressed to achieve better integration of models are incompatibility of spatial scales and time scales (Schmitt and Huber 2006).

A summary of the time and spatial scales for the more important subsystems in an urban and peri-urban water cycle are described in Table 2.2.

Data availability: Water cycle modelling relies on sufficient quality data to enable adequate calibration and evaluation of models performance. Lack of adequate data can be a major constraint in water cycle modelling due to lack of consistency in data collection across subsystem boundaries and within subsystems.

These inconsistencies typically occur in the temporal and spatial scales at which data are collected. Often, data are collected by different agencies responsible for operating these systems, which collect data according to their individual protocols and requirements.

A water cycle monitoring program needs to be designed to collect data on different components of the water cycle in such a way that the data collected can be verified for quality and at the same time can support the assessment of the key sustainability parameters of the system. The design of the monitoring network refers to the selection of sampling sites and temporal sampling frequency to determine quantity and quality properties of water. These features must be selected based on the objectives set for the monitoring network. There are a variety of objectives that can be pursued in monitoring the water cycle such as environmental monitoring, detection, compliance, or research. Environmental monitoring is aimed to understand the characteristics of the water cycle and its variations over time. Detection has the primary objective of identifying specific contaminants and when their concentration exceeds a certain level. The compliance objective is similar to detection except that it is designed to enforce water quality standards and/or progress with water quality remediation works. The research objective requires a more detailed monitoring network of spatial and temporal water quality specifically designed to satisfy a specific research objective.

2.7 Conclusions

With over half of the world's population now living in urban and peri-urban areas and further future growth predictions that it is expected to reach 70 % by 2050, competition for land and water resources is expected to increase rapidly. It is posited in this paper that the urban/peri-urban water cycle consists of a continuum of spatial scales ranging from largely agricultural land to urban areas. This continuum can contain a broad typology of land uses distributed over a catchment landscape as illustrated by the Melbourne Metropolitan and Green Wedges area and the South Creek catchment in Western Sydney.

Water cycle modelling forms a critical part of the decision support systems process for planning future peri-urban and urban developments. As such, water cycle modelling must be designed to meet specific objectives ranging from bulk resource assessment and allocation to description and analysis of individual subsystems. Integrated Urban/Peri-urban Water Cycle modelling involves a range of hierarchical processes associated with individual subsystems including whole-of-water-cycle, water supply subsystem, water demand subsystem, wastewater subsystem and receiving waters subsystem.

Most of the existing models to date operate at a subsystem level and model integration must occur via exogenous data transfer. While it is desirable to integrate these models under a common shell to enable simultaneous modelling and feedback capability, this goal is made more challenging by heterogeneity of temporal and spatial scales across the subsystems boundaries and a similar lack of consistency in data collection and availability. A robust data monitoring program of the entire water cycle is of critical importance to support the modelling effort and provide the data needed for managing the water cycle in a sustainable manner.

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