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Advancing IUWM through an understanding of the urban water balance

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Abstract: Integrated urban water management (IUWM) requires the management of the urban water cycle in sympathy with the hydrological water cycle. Urban systems significantly alter the hydrological water cycle. Under natural conditions the water inputs at any point in the landscape are precipitation and overland flows; while the outputs are via surface flows, evapo-transpiration and groundwater recharge. The large volumes of piped water introduced with the change to an urban setting and the introduction of vast impervious areas strongly impact on the water balance, increasing in-flows and dramatically altering the out-flow components.

IUWM seeks to change the impact of urban development on the natural water cycle. One approach is to establish an inner, urban, water cycle loop through the implementation of reuse strategies. Developing this urban water cycle loop requires an understanding both of the natural, pre-development, water balance and the post-development water balance. Accounting for flows in the pre- and post-development systems is an important step toward limiting urban impacts on the natural water cycle.

This paper investigates urban water balancing and preliminary identification of reuse strategies for the case study of the proposed Tamala Park development in Perth, as the first steps toward an integrated water reuse strategy. The hydrology and hydrogeology of the site are examined. Overland flows are not a feature of the site with rainfall leaving the site as either evapotranspiration or recharge to groundwater. The unconfined Superficial aquifer is identified as suited to aquifer storage and recovery.

Changes to the site water balance due to urbanisation include the significant inflow and outflow of piped water. It is projected that the small allotment sizes proposed would have a beneficial impact on garden water use and hence piped inflow. Water accounting for the developed case showed a decrease in evaporation and an increase in recharge. Reuse strategies should therefore aim to exploit the excess recharge – through groundwater abstraction and roof runoff capture - as a component of an inner urban water cycle loop. Volumetrically, this excess could supply projected in-house uses. Further, if wastewater was reused for irrigation demands the need for mains supply could be eliminated and wastewater discharges halved.

Keywords: *Integrated urban water management (IUWM), water balance*

1. INTRODUCTION

Escalating impacts of a generally drying climate across much of southern Australia has focused attention on the importance of sustainable water servicing practices which account for the needs of the environment (Khan 2008, Mitchell 2006). Integrated Urban Water Management (IUWM) is rapidly emerging as a potential solution to challenges associated with provisioning sustainable water servicing practices in urban areas. IUWM encourages water utilities to plan and manage water supply, wastewater and stormwater systems in a coordinated manner to minimise their impact on the natural environment, to maximise their contribution to economic development and to engender overall community wellbeing and improvement (Maheepala & Blackmore 2008). The principles of integrated urban water management (IUWM) centre on minimising the environmental impacts of urban development through the optimal use of water resources (Sharma *et al.* 2008, Mitchell 2006).

The Tamala Park Regional Council is proposing an urban development at a 200 hectares site located in the north-west corridor of metropolitan Perth. Council has chosen to implement integrated urban water cycle management in the planning and construction of the development's water systems. Council's aim is to minimise demand on imported water by maximising water reuse. This project has provided opportunity to case study a systems analysis approach to the development of reuse scenarios. By conjointly considering the water requirements of both the environment and development, within the overarching context of the hydrologic water cycle, a more sustainable setup for water supply may be realized from the outset.

2. METHODS

A systems approach (Winz *et al.* 2009) has been applied to this work, with the site being analyzed within, and as part of, the hydrologic cycle both prior to and after development. The work described here relates to the problem definition and system conceptualization phases of systems modeling. Changes to the hydrological system arising from the proposed development have been quantified, enabling reuse scenarios to be developed which mitigate against the water imbalances which are generally the outcome of urbanisation. Further model development will enable testing and evaluation of scenarios.

Emphasis has been placed, in the first instance, on developing an understanding of the site hydrology and hydrogeology. Understanding the geological setting and existing hydrology is of relevance to the modeling of the current components of the site water balance – precipitation, runoff, infiltration and evaporation. Further, as on-site reuse systems, including aquifer storage and recovery, are to be considered for the development it is important to identify site constraints and opportunities. The site lies within the Perth Metropolitan area where groundwater has long been exploited for the city water supply and issues with respect to drawdown and saltwater intrusion have been identified in other parts of the metropolitan area.

Pre- and post-development water balance modeling enables an assessment of the water needs of both the natural and developed states. Urbanisation inevitably involves an increase in impervious area and hence an augmentation of surface runoff. Quantification of this change allows potential reuse resources to be identified. In this paper annual volumes are quantified. More refined modeling at a monthly or daily time-step will enable supply opportunities to be more accurately defined.

This work has focused mainly on water quantities with only a cursory consideration of water qualities.

3. HYDROLOGY AND HYDROGEOLOGY

The Perth Basin is a deep sedimentary deposit up to twelve kilometres thick. The upper Quaternary and Tertiary sediments are known collectively as the Superficial formations, which vary in thickness up to a maximum of around one-hundred metres.

Inshore from the coast, rain water infiltrates and collects within the Superficial formations to form the unconfined groundwater system. The Superficial aquifer is a major water resource for the Perth region, supplying water for drinking, irrigation and industry. A relatively small proportion of the superficial groundwater drains downward into the underlying confined aquifer system, while the greater part drains laterally, discharging to the Indian Ocean and Swan-Canning estuary. This continuous process of diffuse replenishment and lateral drainage forms a number of distinct groundwater flow systems that can be recognised as regional groundwater mounds. The most important of these is the Gnangara mound which is the source of around one-third of Perth's potable water supply.

The Tamala Park development site lies between 0.75 and 3 km from the coast on the western margin of the Gnangara mound where the saturated thickness of the Superficial formations is around thirty metres and the depth to groundwater varies from around fifteen to forty-five metres. In this area there are virtually no surface drains to the ocean because the coastal sands are permeable enough to prevent significant surface runoff.

Annual rainfall is of the order of 700 mm. Due to the sandy nature of the soils intercepted rainfall either permeates to the groundwater or is taken up by the vegetation. Trefry et al. (2008) have estimated that evapotranspiration is of the order of 500mm while 200 mm of annual rainfall recharges the groundwater.

4. IDENTIFICATION OF SITE CONSTRAINTS AND OPPORTUNITIES

Groundwater protection zone

The Tamala Park development area is within the Quinns Subarea of the Perth Groundwater Area. The eastern part of the development falls within the Perth Coastal Underground Water Pollution Control Area (UWPCA). The Perth Coastal UWPCA was proclaimed by the Department of Water to protect the public drinking water supply drawn from the western part of the Gnangara Mound. In the study area, Water Corporation has been extracting superficial groundwater from the Quinns borefield since 1999. The current rate of extraction (approx. 13 000 ML/yr) has resulted in around a half-metre drawdown of the watertable throughout the development area.

Spatial variability in groundwater replenishment and aquifer hydraulic properties control the flow pathways and travel times for groundwater to move from inshore source areas to groundwater extraction points and offshore discharge areas. Preferred flow paths within Tamala Limestone may mean that contaminants mobilized into relatively active parts of the flow system would reach the ocean or an extraction point more rapidly than contaminants mobilized into inactive parts.

Saltwater intrusion

The inland extent of the saltwater wedge within the coastal margin of the Superficial aquifer is determined by the slope of the water table, thickness of the superficial sediments, and mixing between groundwater and seawater in the aquifer. Smith et al. (2005) has predicted that the saltwater wedge may extend up to 2 km inshore at the study site; however, groundwater salinity measurements from saltwater-interface monitoring bores north-west of the site indicate that the saltwater wedge is unlikely to extend more than 1 km from the coast. Alternatively, it may only be present further inshore as a very thin tongue of saltwater at the base of the Superficial formations.

Aquifer storage and recovery

The development site lies within a region where the Superficial formation is dominated by the Tamala Limestone deposit. This is a carbonate eolianite that unconformably overlies Tertiary and Cretaceous sediments. It contains various proportions of quartz sand, fine-grained to medium-grained shell fragments and minor clay lenses (Davidson 1995). The limestone typically exhibits secondary porosity in the form of numerous dissolution channels and cavities that are highly conductive to groundwater flow. A karst belt containing solution pipes, caves and sinkholes occurs in the Wanneroo–Yanchep area around five kilometres inland from the coast (Csaky 2003). Elsewhere, Tamala Limestone is commonly described as being cavernous, porous, vughy and broken (Rockwater 2005). Subcrop formations at the base of the limestone include aquitards of the Osborne Formation and upper members of the underlying Leederville aquifer. Tamala Limestone is covered over by Holocene sands along the coastal margin, although coastal exposures of the limestone are common.

Surface infiltration into the Superficial aquifer is considered feasible for the Tamala Park development site. Well injection into the Leederville aquifer is technically feasible but is projected to be expensive and technically challenging.

Artificial recharge into the coastal limestone at Tamala Park would be expected to induce only small water-table responses because the Superficial aquifer has high transmissivity and groundwater elevation is controlled mainly by sea level.

Potential restrictions on surface infiltration include the presence of an impermeable calcrete layer within the limestone and preferential flow through karst features and secondary porosity within the Tamala Limestone. Davis et al. (1991) reported a “very hard silicified limestone layer of thickness 5 to 8 m above the water table” at the Tamala Park landfill located directly south of the development area. If present elsewhere this layer could restrict rapid vertical percolation needed for successful artificial recharge; however, the depth of unsaturated zone above the layer may still be sufficient to allow infiltrating water to move laterally to areas where there is less resistance to vertical drainage.

Preferential flow through the limestone may be an important control on transport and attenuation of contaminants introduced with stormwater infiltration or treated wastewater infiltration. Water quality issues may arise if infiltrated stormwater or treated wastewater can move rapidly from the infiltration site to an extraction bore or into the near-shore marine environment. Detailed studies of treated wastewater infiltration and recovery at the Halls Head Wastewater Treatment Plant in Mandurah (Toze *et al.* 2002) indicated that the infiltration basins and recovery bores were not connected by flow conduits or preferential pathways in Tamala Limestone at that site. Nevertheless, there was clear evidence of conduit flow and associated large transmissivity at the site including tidal responses in the monitoring bores.

5. WATER BALANCE MODELLING

5.1. Existing conditions

A site water balance identifies and quantifies the inflows and outflows which are part of the wider hydrologic cycle. The water balance for existing conditions is depicted in Figure 1. As described above there are no surface flows to or from the site. Calculation of recharge and evapotranspiration volumes for Tamala Park were based on figures from work already undertaken at the landfill site to the south (Trefry *et al.* 2008).

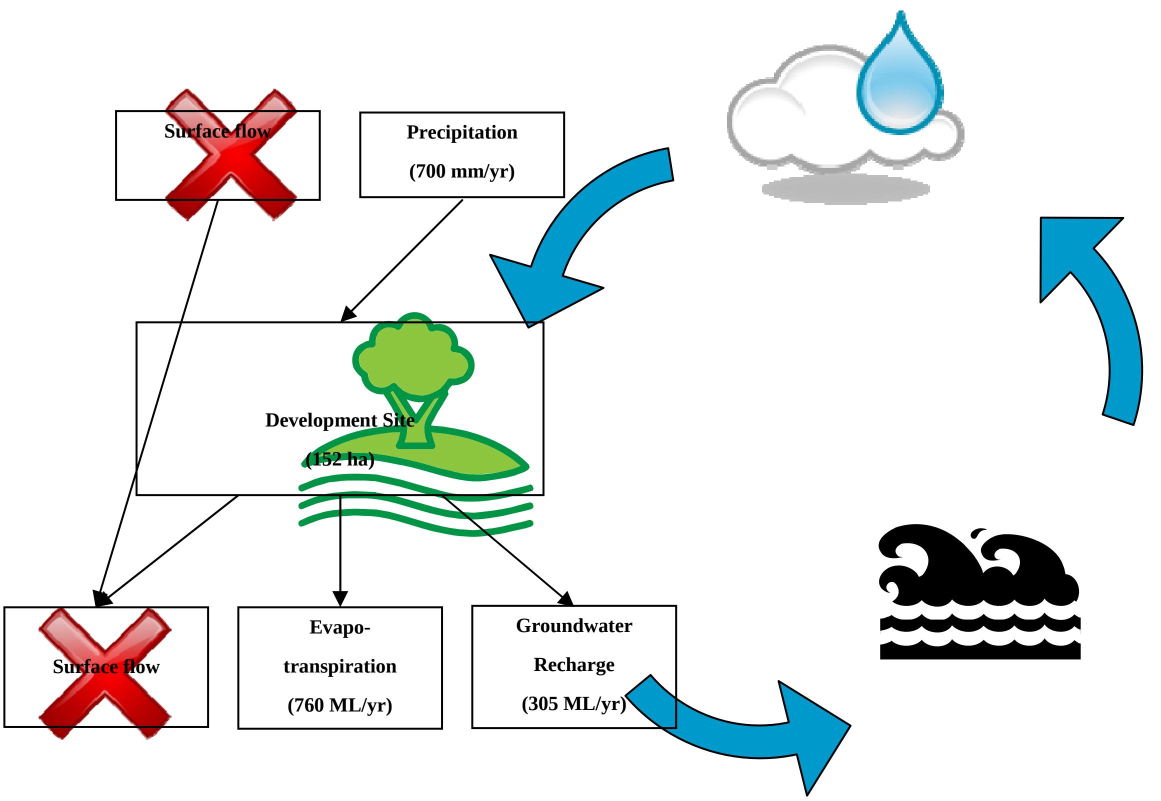

Figure 1. Existing conditions water balance

5.2. Developed conditions

Water balance calculations for the developed conditions scenario, utilised contributing areas estimated from land allocations provided by the Tamala Park Regional Council (refer Table 1). The development proposal projected a total of 2700 dwelling and a total population of 6000. The average allotment size for the proposed development is 375 m^2 and it has been assumed that on average dwellings would cover half the allotment area (Barton 2005), with the remaining area equally divided between pervious and impervious surfaces. A third of the road area has been designated as pervious verge. These assumptions have been endorsed by the development planner.

Table 1. Summary of areas

Description	Total Area (ha)	Impervious fraction (ha)	Pervious fraction (ha)	Building area (ha)
Public open space (POS)	15.177	2.7	12.5	
Urban lots (2700)	102.121	25.4	25.4	51.3
Roads – major	2.000	1.3	0.7	
Roads – POS	2.701	1.8	0.9	
Roads – urban allotments	30.504	19.8	10.2	
Totals	**152**	**51**	**50**	**51**

The Western Australia State Water Plan (Government of Western Australia 2007) cites an average individual water consumption figure of 106 kL per person per year for the city of Perth. The estimated occupancy rate for the development is 2.22 persons per household, giving an average annual household consumption of 235 kL. Research undertaken by Loh & Coghlan (2003) determined an average "in-house" usage for Perth of 155 L/person/day and on the basis of this figure in-house water consumption would amount to 340 ML/yr. This is almost equally divided between contact (bathroom and kitchen) and non-contact (laundry and toilet) uses.

The average allotment size for the proposed development is quite small and this may deliver a reduction in ex-house water use. On the assumption that the dwelling covers half of the allotment and half of the remaining ex-house area is paved, less than 100 m^2 of area is left for lawn and garden. Garden watering rates per m^2 are likely to be higher where householders have only small plots to attend. In the water use study undertaken for Perth by Loh and Coghlan (2003), they were unable to establish a relationship between summer water usage and irrigable area. The majority of their water use data, however, related to irrigable areas greater than 300 m^2 and less than 700 m^2. There were no data for irrigable areas less than 100 m^2. For this research it was assumed that outdoor use would be half the Perth average, or 25 kL/person/year. This translates to an irrigation rate of 560 mm/dwelling/year and a total ex-house usage of 150 ML/yr. An irrigation rate of 150 mm/yr was adopted for the open space watering.

Recharge rates were averaged from the ranges given in Xu et al. (2005) for the Perth Urban Water Balance study and summarised in Table 2.

Table 2. Rainfall recharge in residential areas in Perth (Xu et al. 2005)

Surface Type	Recharge	Comments and assumptions
Roofs	80-90%	Direct subsurface discharge at each lot. Use: 85%.
Paved areas	60-70%	Collected and infiltrated in infiltrations basins Use: 65%.
Lawns and garden areas – rainfall recharge	30-40%	Use: 33%
Allotment lawns and garden areas – irrigation recharge	20%	

The resulting water balance under developed conditions is depicted in Figure 2. A colour-code has been used to highlight changes including increases and decreases in volumes and additional elements. Changes to the water balances have been quantified in brackets. The piped water component has increased volumetric flow by 510 ML. Evapotranspiration decreased by 210 ML (28%) while recharge dramatically increased by 380 ML (125%). The remaining outflow (340 ML) is accounted for in wastewater.

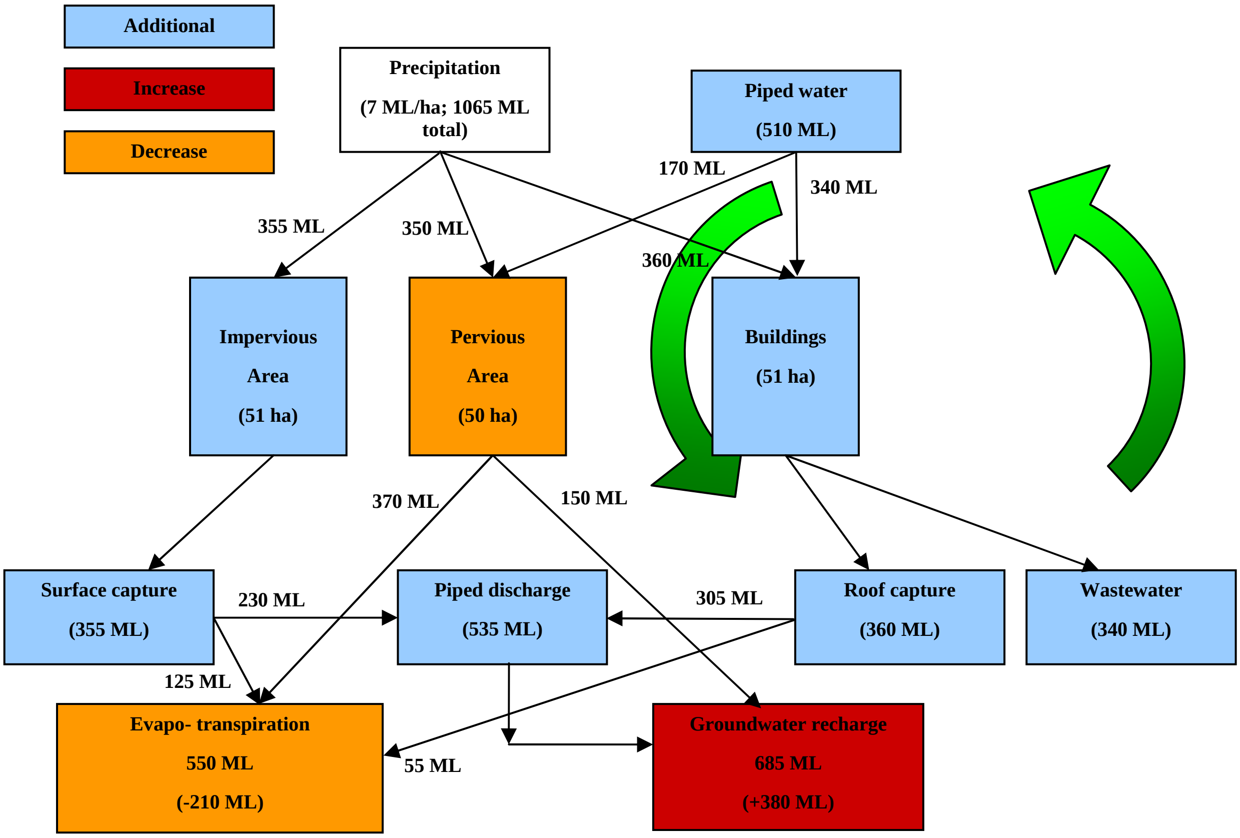

Figure 2. Water balance for the developed (conventional) case

6. DISCUSSION

Comparison of the water balances for the undeveloped and developed cases revealed that, for the geological and hydrological conditions of the study site, and under the assumptions discussed, conventional urban water design would lead to an increase in groundwater recharge and a decrease in evapotranspiration. There would also be an additional piped (wastewater) discharge from the site. These changes would result from the additional inflow of piped water and significant alteration to landuse.

The water balances provide a basis for the development of reuse scenarios. The creation of an "inner water cycle loop" (as depicted in Figure 2), whereby the excess water generated is used to supply the additional water required, works to reduce the changes to the overall hydrologic cycle. This inner, reuse loop should transfer the excess volumes only. A proposed solution, however, could include the generation of additional excess in order to recover it in a second application. For example, treated wastewater could theoretically be used to irrigate special-purpose gardens in order to replenish the evapotranspiration component. This application would result in a further increase in recharge; however this can also be viewed as a storage solution with the added excess being recovered for other applications.

Table 3. Water uses and resources

Water requirements (ML/yr)		Water resources (ML/yr)	
Kitchen & bath:	170	Groundwater:	380
Toilet & laundry:	170	Wastewater:	340
Ex-house:	150		
Parks, etc.:	20		

Consideration of the evapotranspiration component of the water balance in the context of IUWM is an interesting issue. Land surface evapotranspiration is a significant component of the hydrologic budget, but for any change to impact on climate depends on its magnitude and extent as well as the region in question (Shukla & Mintz 1982). With respect to the current development, the estimated reduction in the evapotranspiration component of the water budget is not likely to have any impact on the environment if it were to be ignored. This would not necessarily always be the case, however.

Working on the adopted water use volumes and available water resources (Table 3) an inner (recycle) loop can be developed. The stormwater runoff and groundwater excess would be adequate to supply 100% of in-house uses, though treatment may be deemed necessary. Rainwater tanks may also be considered a more appropriate water storage method for some in-house uses if groundwater contamination is an issue. The wastewater discharge would be adequate to supply all ex-house water requirements.

This scenario would theoretically eliminate the piped inflow and halve wastewater discharge to 170 ML/yr.

7. CONCLUSIONS

Developing an understanding of the hydrogeological context and the changes to the hydrologic water budget associated with an urban development proposal, provides an important beginning to the development of an inner urban (reuse) water loop to mitigate impacts of urban development on the environment.

Water balance modeling carried out so far enables the development of strategies for maximising water reuse at the development scale. The next step is to develop alternative water servicing options in line with the strategies described in this paper, including monthly water balance and life cycle cost analyses of the identified options to establish the preferred water servicing option.

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