Building a DSS to assess the effect of urbanisation on catchment water resources and water quality

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Abstract: Greenfield urbanisation may adversely affect the catchment water balance, including groundwater, wetland and surface water, and may impact on groundwater and stormwater quality. While changes in the water balance are almost immediate, the water quality variation may occur over a considerable period of time. Effect of urbanisation on water quality depends on degree of pre-development water balance alteration and adopted water management practices. A decision support system (DSS) for urban development under complex hydrological/hydrogeological conditions and surface/groundwater interactions is the focus of a multi-agency multidisciplinary research effort. The research aims to reduce nutrient transfer from former agricultural land to surface water, and sourcing the local water resources for non-potable use in quickly developing metropolitan catchments. DSS is based on a number of integrated modelling tools, including GIS and MODHMS models (surface/groundwater interaction model), dealing with water and nutrient fluxes in unsaturated zone, all of which were validated based upon intensive catchment surveys and monitoring programs. A number of water management scenarios were evaluated aiming to improved water cycle management within the proposed new urban developments. Water management considerations included groundwater and stormwater control, water reuse and water conservation.

1. Introduction

Changes in land use often causes alteration of the catchment water balance and may influence surface and groundwater quality, particularly when a large catchment area is designated for redevelopment (Tang, *et al*, 2005). To minimise the impact a catchment-based approach is required to identify the predevelopment conditions and to define the environmental targets which should be met during the land development.

Perth, Western Australia, is one of the fastest growing capital cities in Australia and experiences a range of issues associated with the accelerated land development. The fast growth of metropolitan area forces development of catchments affected by inundation, occurrence of wetlands as well as high nutrient concentration in both surface and groundwater, generated during decades of agricultural activities.

Additionally the population growth causes increase in water demand adding pressure on the existing water supply sources. More often new urban developments employ decentralized water supply systems, exploring opportunities of water reuse or local groundwater utilization to meet at least for the non-potable water demands such as garden irrigation or toilet use.

The paper describes outcomes of the research which provide scientific and technological support to deliver socially acceptable and environmentally beneficial water management options, supporting urban development and non-potable water supply sourced from local natural water resources. These outcomes include

- Establishment of the fundamental relationships between the external forcing (i.e. meteorological conditions, land use, water management) and surface, ground water and unsaturated zone water dynamics
- Development of forecasting tools/models aiming for prediction of future interactions between surface and groundwater in the physical and water quality context under various scenarios of land use and climate change
- Development of in-situ treatment technologies reducing the nutrient concentration in urban drainage, control nutrient export to receiving water bodies (conservation wetlands, estuaries) and accordingly reducing the risk of eutrophication and associated mitigation costs
- Guidance on methods to maintain environmental flows in receiving water bodies
- Integration of the above with the social and economics constraints of the water management options in a framework for identification and selection of socially acceptable and environmentally beneficial water management options
- Advice on ways to increase utilisation of locally available natural water resources reducing dependency on centralised water supply schemes to 40-60K/capita

In what follows we address the key features of the decision support system (DSS) developed to facilitate urban development in water sensitive areas. While we outline all the key steps in development of the systems, some of the elements found to be critical to ensure the success of the study are presented in more details:

- Scientific challenges to be addressed in extensive field work and associated computer modelling
- Hydrological / hydrogeological and water quality considerations and using the selection of appropriate BMPs
- Process developed to facilitated transparent development of targets to insure their endorsement by both the regulatory authorities and developers

The above selected aspects were found to be critical ingredients in converting the knowledge gained by intensive scientific research into the practical and transparent framework which is to be used be stakeholders in the future.

2. The systematic approach to decision making for catchment urbanisation

Schematic presentation of the adopted approach is shown on Fig. 1, reflecting inheritance and evolution of decision making process in assessing the natural system and providing guidance to stakeholders, ensuring successful development of water sensitive urban development.

The key components of the approach can be summarized as follows.

1. Recognition of time progression in building of knowledge depository on catchment hydrological and water quality processes, based on appropriate data acquisition and process-based computer modelling
2. Definition of scientifically justifiable environmental targets for urban development, agreed by all stakeholders
3. Identification of appropriate Best Management Practices (BMPs) which will ensure compliance with the identified targets
4. Adaptation of generic environmental targets to reflect site specific proposed land, water and nutrient management options for individual and multiple developments

To reflect the complex nature of the underlying system a sophisticated catchment monitoring program was developed covering both surface and groundwater fluxes and quality, complemented by robust, process-based computer modelling. The purposely built information system allows systematic knowledge capture, enabling timely knowledge transfer to stakeholders.

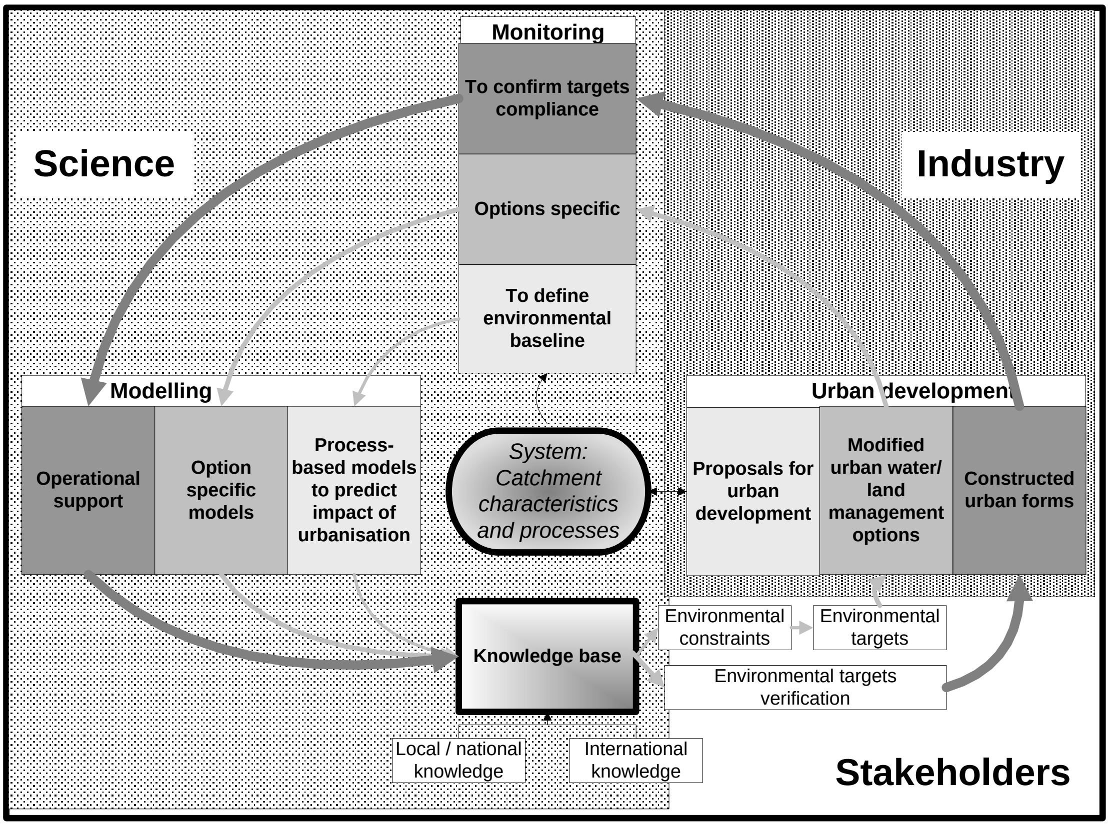

Figure 1 - Schematic of the System approach

3. Case-study: Southern River Urbanisation

The approach was developed on a case study of the Southern River catchment (Perth, Western Australia) (Fig 2). The catchment is one of the fastest developing regions in the metropolitan area where urban expansion is challenged by many environmental issues. They include shallow groundwater tables, high nutrient concentrations in surface and groundwater, inundation, conservation wetlands, proximity to a groundwater supply mound and to the Swan-Canning Estuary. These complex environmental settings characterise the catchment as extremely sensitive to alteration in water management.

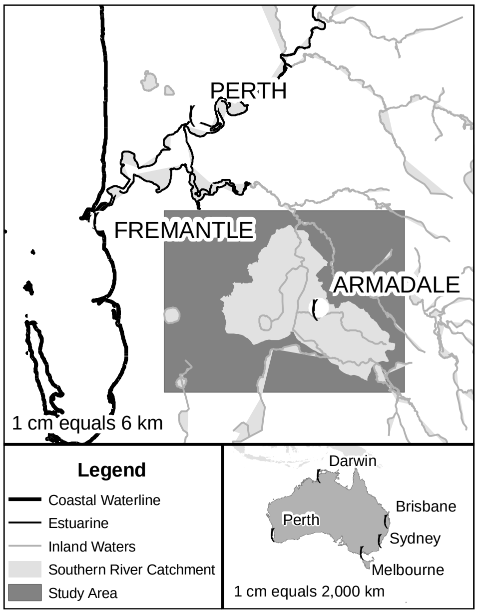

Figure 2 – Location map

The catchment (198 km^2) is located near the eastern edge of the Perth basin immediately adjacent to the Archaean Craton margin and Darling escarpment in the East. The elevated upland area on the south–east (approximately 41 km^2) includes the upper reaches of the river. The rest of the Southern River catchment is mainly a flat low-lying area of Quaternary fluvial and aeolian deposits 20 to 60m thick underlain by Mesozoic sediments. The Quaternary deposit consists of aeolian Bassendean Sand predominately occurring in the west, and Guildford Formation, predominantly clays of alluvial origin outcropping within the eastern part of the catchment adjacent to the Darling Scarp. Low surface gradient and limited drainage capacity of local subsoil cause land inundation, and establishment of wetlands.

There are two major land uses in the low-lying part of the catchment: urban and semi-rural. The currently urbanised areas include suburban housing and infrastructure on the northern and eastern boundaries of the catchment, and cover less than 30 km^2. The remaining rural part of the Southern River catchment include State Forrest area in the hills, remnant vegetation (conservation category "Bush Forever site") and cleared land used for hobby horticultural and livestock farming (Fig. 3). As is typical for the Mediterranean climate, rain mainly falls during winter month, while summer months are usually dry and warm. The annual average rainfall (1989-2006) is 858mm to 897mm at rain gauging stations located within the catchment.

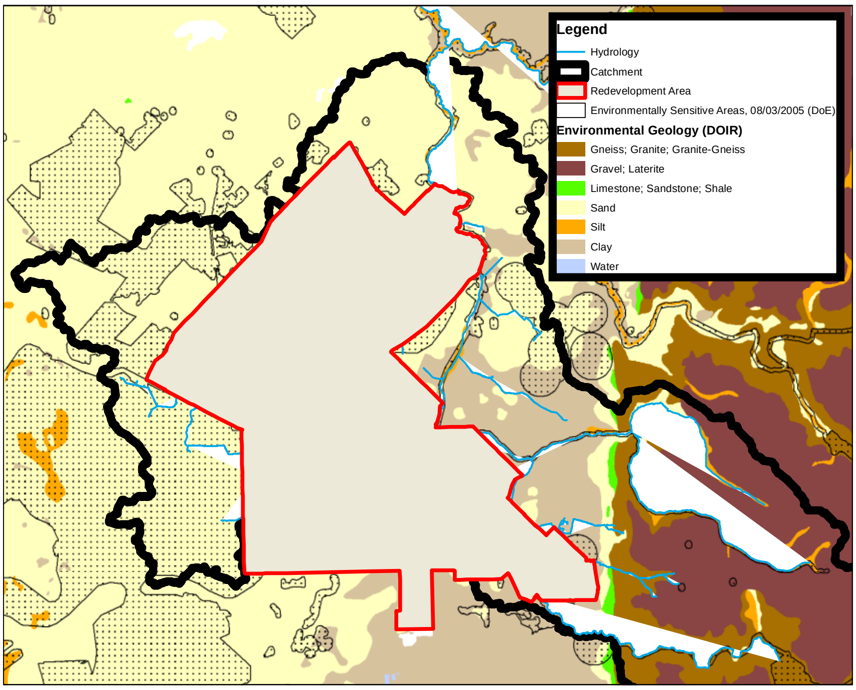

Figure 3 – Environmental sensitive areas and location of proposed urban development

The Southern River discharges in the Swan-Canning Estuary, which is already suffering from ongoing threats due to eutrophication; the river is currently the second largest contributor of Phosphorous and Nitrogen load to the estuary. The key catchment characteristics relevant to urban development are: a high groundwater table (<2mBGL) with extensive water logging during wet seasons associated with the Superficial Aquifer; high nutrient concentrations in shallow groundwater (TPmean=1.75mg/l up to 10mg/l; TNmean=4.85mg/l up to 250mg/l); high export rate arising from current and historical land use (TP losses >0.3kg/ha/year) and the requirements for maintenance of existing environmentally sensitive wetlands.

The schematic presentation of the multiple components of the complex hydrological system in the catchment is given on Figure 4. The key features include complex interaction between surface and groundwater, charactered by a spatial and temporal variability, intensive water abstraction in the catchment from surface and groundwater sources, leading to a significant seasonal variation in water fluxes, levels and water quality. Mobilization of various nutrients, already stored in the predominantly sandy soil with virtually no retention capacity, at different times and at different concentrations are a function of the complex interactions between the surface and groundwater.

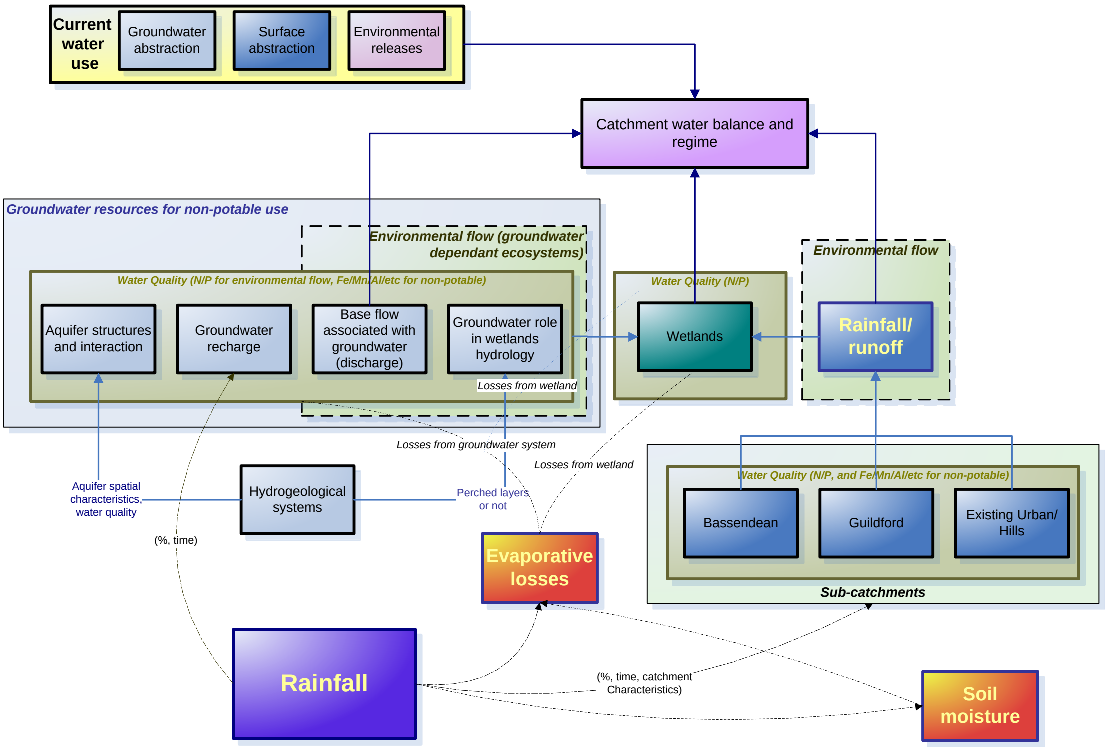

Figure 4 – Interaction in catchment water system and water use

3. Key challenges

The main research goal is to evaluate current interaction, and forecast future interactions, between surface and groundwater in the physical and water quality context under a range of land use types and climate change scenarios. This scientific challenge needs to resolve a complex web of physical/chemical/biological interdependencies that are usually understood only under well controlled or simplified conditions.

The key scientific challenges tackled by and advanced with this research can be summarised as follows:

- identification and quantification of regional and local processes controlling the surface and groundwater interaction
- quantification of the role of the interaction in the physical sphere to the surface and groundwater water quality
- prediction of future interactions between surface and groundwater in the physical and water quality context under the land use and climate change scenarios
- development of treatment technologies reducing the nutrient load in urban drainage

The very nature of the task where these interdependencies have to be understood and quantified over a considerable spatial extent and over significant time (months and years) requires a systematic approach, in both capturing the relevant data and analysing the underlying processes to ensure the correct interpretation of current, and in particular prediction of the future, behaviours of the natural system. The considerable spatial extent and seasonal nature of the natural system requires a systematic and scientific approach to establish the key underlying processes in order to be able to:

- Develop an appropriate monitoring system that can capture all of the key processes; including high temporal resolution water quality monitoring in river, groundwater level observation water quality in multiple nested bores, nutrient cycle in seasonally saturated zone and water quality in selected wetlands
- Develop a modelling capability to address the complex interaction between surface and groundwater and also predict the impact of land use change of catchment fluxes and water quality; a process-based modelling approach was selected and the adopted suite of models range from the simple allowing simulation of an individual process such as unsaturated zone fluxes, catchment connectivity and event response models, wetland water and mass balance models to a complex process-based model (MODHMS, Panday and Huyakorn, 2004), simulated the complexity of the system but also verified by the outcome of monitoring and the results simple models and used for a predictive simulation of land use alteration and climate change (Fig. 5)
- Develop a data acquisition/processing and storage system/methodology that will ensure and facilitate successful assessment of these processes; these not only include data management (spatial, attribute, and time series; observations or synthetic data), but also data processing, storage within adopted data modelling defining data structures, relationships, integration and services (data and tools accessibility and reporting), which are tailored to the defined clients

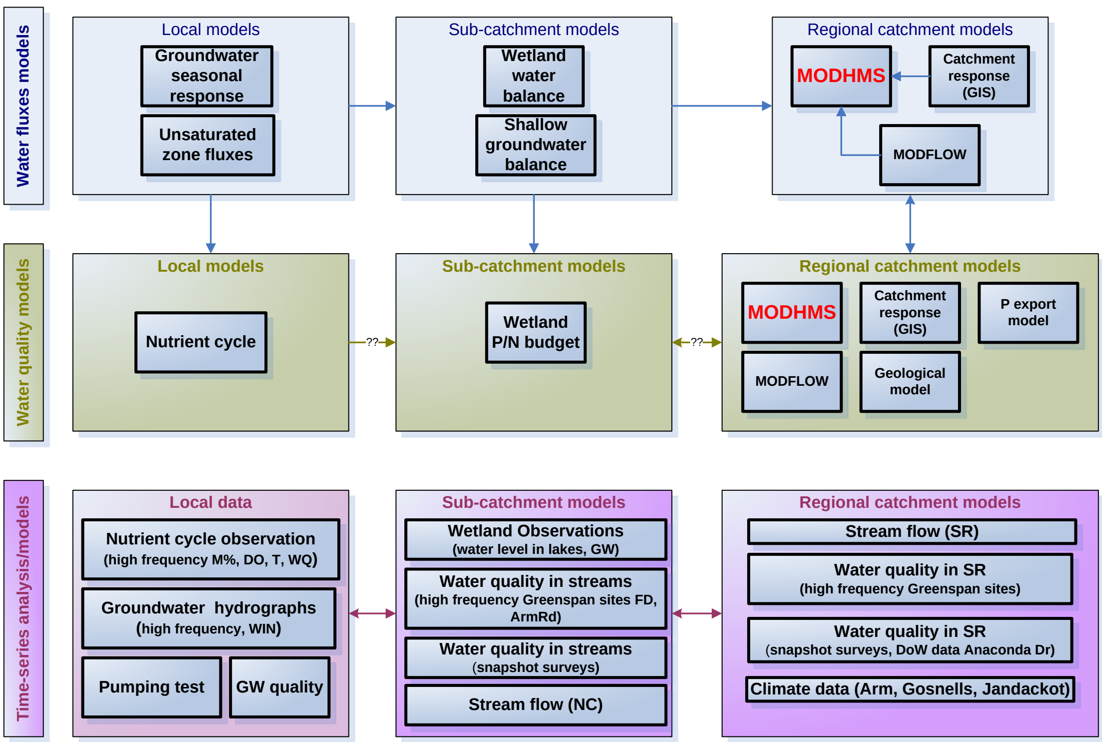

Figure 5 – Adopted modelling approach supporting DSS

- Communicate the complex findings amongst the team members who may be the specialist in their respective disciplines, but are not necessarily able to comprehend the complex web of interactions. Whilst a challenging task in itself, this is considered a particularly important aspect of this research as it will ensure the transferability of the methods and knowledge developed in this project to other localities.

5. Development of environmental targets for urban development

5.1 *Effect of urbanisation on catchment system*

The environmental targets for new urban development need to be defined in order to provide an adequate control of a potential increase in peak flow during storm events, deterioration of water quality (both surface and groundwater), potential impact on environmental flow and preservation of ecological health within local water ways and wetlands. Critical considerations in environmental target development include

- Well defined predevelopment catchment conditions and fluxes
- Evaluation of proposed land/water/fertiliser management option for new development, including density of new development, area designated to public open space and required irrigation and fertilisation, water supply and reuse schemes (centralised or decentralised, sourcing grey water, local groundwater or rainwater tanks) and the effect of their implementation on catchment conditions
- Temporal nature of water quality targets dependant on the release rate of legacy nutrients within redeveloped areas, the rate of urban development in the catchment and response to new sources of nutrients introduced by new urban development

The key characteristics of predevelopment catchment conditions and their implication to urban development are given below followed by an example of adopted methodology for definition of the environmental target.

Based on the outcomes of the monitoring and modelling, the current effect of the redevelopment area on water quality and flow in the Southern River outflow from the redevelopment area is controlled by a number of factors.

Environmental condition	Catchment response
Contribution of the redevelopment area to the Southern River flow	The current overland flow and groundwater discharge from the redevelopment area are extremely low and are below the estimation accuracy of the river flow. Due to the flat landscape and multiple dunes, the

	redevelopment area is hydraulically disconnected. As a result catchment areas, contributing to the river and drains flow, are limited to within close proximity of the waterways.
Current inundation processes within the redevelopment area	Due to the flat relief, shallow groundwater occurrence and a lack of hydraulic connectivity between various areas, the redevelopment area is prone to inundation. Water accumulated in the inundated areas and within the shallow layers of groundwater systems is lost to evaporation.
Current water quality in the redevelopment area, both surface water and groundwater	Water quality in the open water and groundwater within the redevelopment area shows high nutrient concentrations (both Phosphorus and Nitrogen). Due to the extremely low discharge rate from the redevelopment area, impact on water quality in the major streams within the redevelopment area has not been detected.
Presence of wetlands	The wetlands provide an effective buffer for suspended materials and nutrients in surface water, discharging from the catchment. However, nutrient accumulation within the wetland system is expected.

The magnitude of the urbanisation impact on catchment fluxes and water quality largely depend on the density of new urban development, the extent of local water resources used as water supply, climate variability, and nutrient management in new urban forms. The nature and scale of these possible changes are likely to vary over time. Several conditions are outlined below.

Environmental condition	**Catchment response**
Contribution of the redevelopment area to the Southern River flow	The discharge rate from the area will increase due to: - an increase in the connectivity between the redevelopment area and local surface water network and - the reduction in evaporative losses, control of the shallow groundwater level and surface inundation.

The risks in water quality deterioration may vary during various phases of the urban development	Nutrients flushing from the shallow groundwater may increase the risk of higher nutrient load in the urban drainage during the first few years following the individual developments. The long term variation in water quality of the urban drainage will be dependant on adopted water and nutrient management in new developments.
Presence of a wetland	Higher flow from the catchment resulting from urbanisation may increase flushing of the nutrient accumulated within the wetland system.

The knowledge of the process governing the variation in the catchment water balance and nutrients sources and pathways within new urban development may support the environmental targets developments and opportunities for reduction in nutrient loads. As an example the constraints and opportunities to control Total Phosphorous (TP) load in urbanised catchment is summarised in Table 1, with the opportunities being soil amendments, other water quality BMPs, e.g. in-situ treatment (drains) and control of nutrient input in new urban forms.

Table 1- Constraints and opportunities to control TP load in urbanised catchment

Factors affecting existing nutrient loads		***Factors causing alteration in nutrient loads***	***Opportunity for reduction in nutrient loads***
Soil	Urbanisation	Legacy nutrients pool	**Soil amendments**
		Soil alteration (import)	
Catchment hydrology		Increase in stormwater generation	**BMPs e.g. in-situ treatment (drains)**
		Increase or reduction in groundwater recharge (depending on stormwater management measures)	
		Reduction in evapotranspiration	
		Drainage network alteration	
Nutrient input		Domestic gardens, Public Open Space	**Control of nutrient input**
		Sewage or septic tanks	
		Grey water reuse for garden irrigation	

5.2 *Example of target definition*

One of the important outcomes of this study was the identification of appropriate environmental targets that would ensure successful management of the water resources by the proposed urban development. The reported framework is currently addressing the definition of nutrient release targets and environmental flow targets. The letter is predominantly constrained by the requirement to maintain the predevelopment water balance in conservation category wetlands and river baseflow; and aim to facilitate regulation in groundwater abstraction for non-potable water supply and stormwater management. The approach to development of nutrient management targets is given here in more details.

It is proposed that the nutrient management targets for an individual development or for a group of developments are aligned with the catchment scale targets, such as river discharge (Q) and water quality in terms of nutrient concentrations or loads (C). The latter is expected to be defined by water regulatory authorities based on conditions in the receiving waters required protection (in the reported case the Swan Canning Estuary). When such targets are not fully developed, the nutrient load in predevelopment conditions could be initially used for the regional targets. For example in Southern River the annual Total Phosphorous (TP) load, Soluble Reactive Phosphorous (SRP) load and their relationship with the total annual river discharge is shown on Figure 6.

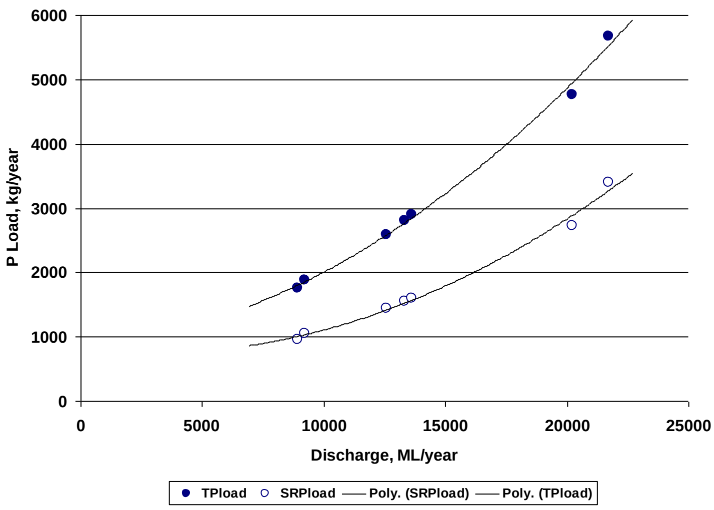

Figure 6 – TP and SRP annual load in the Southern River as a function of total annual river discharge

Undertaken catchment monitoring and modelling allowed both defining the baseline conditions, *i.e.* current catchment loads, and estimating current contributions from individual sub-catchments to river nutrient load at various time scales (annual, seasonal, monthly, and in some cases daily). The predictive modelling allows estimating alteration in sub-catchments discharge associated with urbanisation, which is further used to define targeted reduction in the concentrations as

$$c_i^u = q_i c_i / q_i^u \qquad 1$$

where q_i and c_i are discharge and nutrient concentration of the drainage from a unit area in the predevelopment conditions, q_i^u and c_i^u are discharge and nutrient concentration of the drainage from a unit area in the post-development conditions

The approach also allows identifying the major contributing nutrient sources in the new urban landscape such as irrigated areas, roof runoff, road runoff and others, which assists the selection of mitigation options/BMPs that provide maximum return in terms of nutrient load reduction. The following example demonstrates the approach to estimate average TP load targets in one of the larger redevelopment area (Wungong Urban Waters, 15km^2) in the Southern River catchment. The predevelopment is low lying sub-catchment currently contributing on average 165kgTP/y as shown in Table 2. This estimation was based on an average q_i =245ML/y discharge rate from the area and TP concentration c_i =0.67mgTP/L (SDV=1.84mgTP/L). The proposed new development is characterised by the following land use

Roof	34%
Paved	14%
Lawn	19%
Garden	5%
Native	18%
Road & Reserve	8%
Open Water	2%

Table 2 - Verification of TP targets and affect of selected BMPs on TP load in the urban development

	Pre-development		**Post-development**				
			Total	**Sources contribution**			
				Native / Conservation areas	**Irrigated fertilised areas**	**Roof runoff**	**Other hard surfaces**
Annual discharge volume (ML)	245		5000	879	879	2109	1172
TP (mg/L)	0.67 (Std 1.84)			0.1*	2 (0.5-10)*	0.2*	0.1*
TP target	***Load*=165kg/y (max 330kg/y)**			***Reduction target* 95% (min 89%)**			
Management options		**Achieved reduction %**	**Total TP load kg/y**	**Native / Conservation areas**	**Irrigated fertilised areas**	**Roof runoff**	**Other hard surfaces**
No BMPs	Load (kg/y)	0	2886	88	**1641**	422	118
	Contribution (%)			2	**75**	19	3
Soil amendments (reduction in TP concentration in leakage from irrigated area)	Load (kg/y)	75	720	88	82	**422**	118
	Contribution (%)			8	12	**68**	10
Roof runoff reuse (reduction in runoff from the roofs: rainwater tanks)	Load (kg/y)	80	583	88	82	295	118
	Contribution (%)			15	24	43	19
Groundwater use for non-potable water supply to increase aquifer storage (SY=2GL)	Load, kgTP/y	92	220	44	44	148	59
	Contribution %			15	24	43	19

* typical concentration in urban water streams without adoption of BMPs (*e.g.* Gobel et al, 2007)

According to modelling using MODHMS, urbanisation will result in significant increases in the annual discharge rate from this catchment, and up to q_i^u=5GL/y is expected to be discharged from the redevelopment area. Such an increase in annual discharge is defined by the requirement to drain a significant volume of water currently causing the land inundation; and by changes in evaporative losses from the area due to urbanisation.

It follows from the analysis that TP concentration (c_i^u) in the drainage from the redevelopment area must be reduced by 89-95% in order to maintain the predevelopment TP load. Alternatively reduction in post-development TP load may also be achieved by reduction in the volumes of urban discharge by introduction of water reuse options.

It is shown in Table that management of TP concentration in urban water stream provides greater reduction in TP load than available options for reduction in urban runoff discharge. As demonstrated by the example soil amendments allow reducing TP concentration in leakage to shallow groundwater table from 2mg/L to 0.1 mg/L (Douglas, *et al*, 2004) and therefore 72% TP load reduction may be achieved. Roof runoff and groundwater reuse allow further reduction in TP load to 92%, which is within the range of the desired TP load control.

Conclusions

The key findings of this study in the context of building the DSS can be summarised as follows

- While technical aspects required significant effort and attention to details to balance complex natural processes, and time and budget constraints, the key aspects of the study were development of transparent methodology that facilitate clear communication of complex results to key stakeholders
- Original targets required a critical assessment to closely reflect existing environmental conditions and land/water/nutrient management in the new development
- A transparent procedure was developed to ensure endorsement of the final targets by the stakeholders
- Purposes built tools were required to communicate study findings to the stakeholders. This was critical for engagement to ensure efficient use of study finding in the decision making process by regulators and developers. This tool encompassed both current conditions and future likely options for water management of the proposed developments.

The approach also allow Triple Bottom Line benefits, supporting **economic benefits** such as better costs control by urban development industry when effective and site specific BMP's are selected or prevention of unnecessary costs by the local and state government to deal with deterioration of receiving water environment after development is completed, **environmental benefits** such as definition of sustainable groundwater yields for non-potable water supply within the constraints related to environmental flow or improved water quality by introduction of new material for soil amendments and in-situ urban drainage treatment; and **social benefit** by establishment of community acceptability of sources with different water quality aesthetics and the degree to which people are prepared to comply with developers' proposed usage controls and comparative costs, but also improved government policy and regulations for targets in the nutrient control for new urban development and alternative water supply schemes

Acknowledgement

The research was undertaken within the Swan Future project (funded by CSIRO National Flagship Research *Water for Healthy Country*) and the project "Investigation of Techniques to Better Manager Western Australia's Non-Potable Water Resources" (funded by the Western Australian Premier Water Foundation).

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