Integrated urban water management for residential areas: a reuse model

A. B. Barton and J. R. Argue

ABSTRACT

Global concern over growing urban water demand in the face of limited water resources has focussed attention on the need for better management of available water resources. This paper takes the “fit for purpose” concept and applies it in the development of a model aimed at changing current practices with respect to residential planning by integrating reuse systems into the design layout. This residential reuse model provides an approach to the design of residential developments seeking to maximise water reuse. Water balance modelling is used to assess the extent to which local water resources can satisfy residential demands with conditions based on the city of Adelaide, Australia. Physical conditions include a relatively flat topography and a temperate climate, with annual rainfall being around 500 mm. The level of water-self-sufficiency that may be achieved within a reuse development in this environment is estimated at around 60%. A case study is also presented in which a conventional development is re-designed on the basis of the reuse model. Costing of the two developments indicates the reuse scenario is only marginally more expensive. Such costings however do not include the benefit to upstream and downstream environments resulting from reduced demand and discharges. As governments look to developers to recover system augmentation and environmental costs the economics of such approaches will increase.

Key words | integrated urban water management, model, residential, water reuse

A. B. Barton
CSIRO Land and Water,
Waite Road,
Urrbrae 5064, SA,
Australia
E-mail: *Annette.Barton@csiro.au*

J. R. Argue
Urban Water Resources Centre,
University of South Australia,
Mawson Lakes 5095, SA,
Australia
E-mail: *John.Argue@unisa.edu.au*

INTRODUCTION

It is widely accepted that moving toward more sustainable urban water practices involves moving away from the inefficiencies of a single quality potable supply for all uses, to optimising resources and treatment processes for specific applications (Okun 2000; Toze 2006; Weber 2006). The corollary to this is the need for the decentralisation of systems and greater application of local treatment and storage measures in order to minimise the costs of transportation and distribution (Hermanowicz & Asano 1999; Fane *et al.* 2002). It is important with this approach, however, that health standards are not compromised (Toze 2006). Greater investment in maintenance and monitoring is seen to improve reliability and reduce pathogenic risk (Fane *et al.* 2002) and this investment is usually provided by regulated agencies (Okun 2002). Hence reuse models at the single household scale (e.g. Terpstra 1999) generate concern with respect to health risk because they are typically self-managed. The Weber DOT-NET model (Weber 2004) proposes the integration of wastewater reuse into the urban environment at the neighbourhood level and above. Systems at these scales, being more publically owned and managed, enable social values with respect to risk to be better maintained.

The DOT-NET model (Weber 2004) is essentially a strategy for urban water recycling, which addresses a number of the main challenges of reuse. (1) It facilitates optimal use of resources while (2) successfully merging reuse systems with conventional infrastructure in a manner

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which (3) maintains health risk standards and (4) amenity norms. It is, however, essentially limited to reuse of wastewater generated from urban uses. Stormwater runoff, which is generally of a higher quality than wastewater (Nolde 2007), is not directly included.

Stormwater runoff volume, from the paved surfaces and roofs of urban areas, can be significant (Niemczynowicz 1999) and hence is a valuable resource–especially in environments where water resources are limited. Niemczynowicz (1999) points out that 100 mm on a 1 km^2 impervious surface can potentially supply the annual water requirement of around 1,800 people at a rate of 150 L/day. Furthermore, being generally of a higher quality than wastewater, suggests more cost effective systems are possible. Depending on location, minimal treatment is required for roof runoff to be used as a potable supply whereas significant treatment is essential for that portion of wastewater which is to augment the potable supply in the DOT-NET model.

There is therefore scope to add to existing work and investigate models for integrating both stormwater and wastewater systems into urban development. This paper concentrates on the residential sector of the urban domain. It investigates how reuse systems can be integrated into a development and interconnect with conventional systems, while maintaining amenity. It also explores some of the sustainability and cost implications of the proposed model. To do this realistically, the model has been applied to an Australian metropolis, Adelaide, where the climate is semi-arid.

METHOD

The approach applied in this work has been to firstly establish a reuse paradigm as the framework for the subsequent development of a reuse model for residential development. The aim of the reuse paradigm is to provide a method for allocating available water resources to residential uses and is based on the "fit for purpose" concept of matching water type to use in order to minimise health risk and treatment requirements. A reuse model is subsequently developed which endeavours to apply the reuse paradigm at the neighbourhood level in a practical manner that minimises collection, transportation and storage requirements and maintains amenity. The intention of this approach is to increase the cost efficiency of reuse by minimising all types of water infrastructure.

To estimate the potential of the model to reduce demand on external supply sources a water balance analysis is undertaken. Using an historical rainfall record, knowing the annual demand quantity and pattern, and fixing storage capacity, the level of reuse can be determined.

A case study is undertaken, involving the application of the model to an actual subdivision, to demonstrate the applicability of the reuse model and explore the implications for development costs. The approach here was to take a conventional suburban development and redesign it on the basis of the reuse model. A comparison is then undertaken of the development costs of the conventional and reuse scenarios.

All aspects of this approach demand a setting, hence the city of Adelaide, Australia, has been used for the case study. Adelaide is a coastal city which is situated on a plain underlain by sedimentary aquifers. Annual rainfall is around 500 mm with almost 70% falling during the winter (April–September) months. The average daily maximum temperature ranges from 15°C in winter to 28°C in summer–when pan evaporation can average more than 7 mm/day.

A WATER REUSE PARADIGM

The water reuse paradigm developed as part of this study is depicted in Figure 1. In the development of this paradigm both resource quantities and qualities have been considered in conjunction with water use requirements.

The categorisation of both the available urban water reuse resources (as roof runoff, surface runoff, and wastewater) and residential uses (as in-house, ex-house and recreational space) has been made with a view to minimising reuse infrastructure. The more resources and uses are partitioned, the more complex the transportation and storage needs; and this translates into additional development costs. The resource categories have been simplified on the basis of collectible "streams"; while uses have been partitioned on the basis of discrete demand regions within

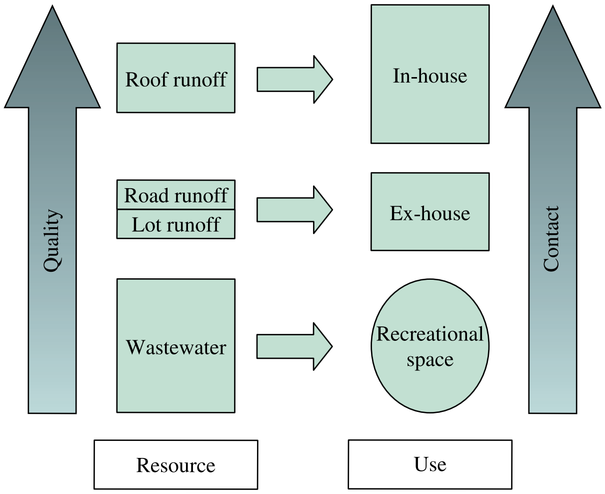

Figure 1 | A water reuse paradigm.

the residential domain. Weber's DOT-NET (2004) model appears to follow a similar approach.

The quality aspects of the three reuse resources have been explored in Barton (2005) and are briefly described here. In Australia roof runoff, collected in rainwater tanks, has wide community acceptance as a good quality potable water supply. Water quality testing has failed to detect those pathogens which pose a serious risk to human health (Cunliffe 1998) however there is evidence to suggest that roof runoff does not necessarily meet the Australian Drinking Water Guidelines (NHMRC 2004). Cunliffe (1998) emphasises the need for proper maintenance of roof catchments and tanks to safeguard quality, however, where the water is to be used for drinking some form of treatment or disinfection at the point of entry may be appropriate (Daiper 2004).

Urban surface runoff is inferior in quality to roof runoff. There is a wide range of contaminate sources within the urban landscape hence some form of treatment is required before surface runoff can be used for domestic purposes. However, with removal of gross pollutants and suspended solids in treatment systems such as grass swales and bioretention strips, stormwater runoff is considered to be of adequate quality for non-potable uses (Wong 2006).

While the toilet is obviously the main source of gross faecal contamination in domestic wastewater, some degree of faecal contamination can potentially occur in every in-house water using activity (Millis 2002). Concentrations of human faecal indicator bacteria even in greywater can be high enough to indicate a health risk (Jeppesen 1996). Any wastewater reuse application would require some treatment and disinfection for pathogenic and odour control. Wastewater reuse is best suited to non-contact applications such as parks and gardens irrigation (dripper or underground) if treatment is to be kept to a minimum.

Allen (1993) provides annual quantity estimates for residential uses and discharges for a series of dwelling types sited in the Adelaide region. The values adopted for the paradigm are for medium density development, where the individual allotment size is of the order of $300\,m^2$. Quantities are represented in Figure 1 by the size of the objects. The recreational space demand, however, is shown as a circular shape to indicate a non-quantified amount.

Two important trend indicators are included in the figure. One is a scale of increasing quality which is linked to the available resource quantities; the other a scale of increasing contact level which is linked to residential uses. As discussed earlier, for any reuse scheme it is important that the health risks be minimised. A relative measure of risk is the level of human contact associated with a particular use, and whilst it can be argued that all three use categories include both contact and non-contact applications, overall, there is a increasing level of contact from the first (recreational space) to the last (in-house) category.

The water reuse paradigm allocates resources to uses on the basis of both quantity and quality. Firstly, the highest quality resource is assigned to the highest contact use hence roof runoff has been assigned to in-house uses. The available quantity of roof runoff equates to about half of in-house demand, hence the in-house application more than accounts for this resource and supplementation is required. Surface runoff (comprising allotment runoff and road runoff) equates to around 75% of ex-house uses and hence is also fully utilised in this application. Wastewater has been assigned to open space irrigation. The level of use of this resource is dependent on the physical characteristics of the irrigation area.

The reuse paradigm provides a framework for building a reuse model where treatment requirements and health risk are minimised. Application of this paradigm in practice involves a residential design with collection, treatment, storage and distribution facilities.

AN URBAN WATER REUSE MODEL

To advance the economics of reuse, infrastructure requirements need to be kept to a minimum. Where roof runoff is to be used as an in-house water supply the simplest method for collection and storage is via gutters and downpipes to a tank. In Australia roof runoff is generally considered to be potable so long as gutters and tanks are properly maintained (Cunliffe 1998).

Surface runoff is diffuse in nature and grass swales and bioretention strips are a simple means of achieving both collection and treatment needs (Wong 2006). Storage can be provided in underground tanks, however, in many situations, the local aquifers have water storage potential. Aquifer storage and recovery (ASR) of stormwater runoff has been successfully pioneered in the Adelaide region (Dillon & Pavelic 1996; Chaudhary & Pitman 2002) and provides a relatively economic storage method.

Where wastewater reuse is in a non-contact application such as the irrigation of parks and gardens treatment can be kept to a minimum. Compact, small-scale, wastewater treatment systems are commercially available which produce clear irrigation water from raw sewage and can be networked for housing development (e.g. the widely acclaimed Biolytix System®: Porteous 2005; Taylor 2006).

The standard "linear" arrangement of streets and allotments of a conventional, medium density, development does not easily accommodate the infrastructure for roof runoff and wastewater management discussed above. As for many existing reuse schemes, considerable transfer infrastructure, including holding tanks, pumps and pipes, is required. To minimise such infrastructure there is a need for some common spaces to be sited in reasonably close proximity to dwellings.

Conventional layouts also pose issues for swale location and performance. Swales, being linear in nature, are ideally placed within the road reserve where they can take the place of gutter and pipe systems, however it would be difficult to accommodate them in the narrower access roads of a contemporary development. As well, the numerous overpasses required to give access to individual allotments, could result in large amounts of backfilling which would severely impact on the storage and treatment capacity of any swale; alternatively, bridges would be very costly.

The reuse model, illustrated in Figure 2, has emerged as one application of the water reuse paradigm. It proposes a clustering of dwellings around a cul-de-sac adjacent an open space area, enabling infrastructure to be minimised and swale crossings to be significantly reduced.

The model includes in-ground tanks to serve as the water supply storage for in-house uses. Water from the roofs of the

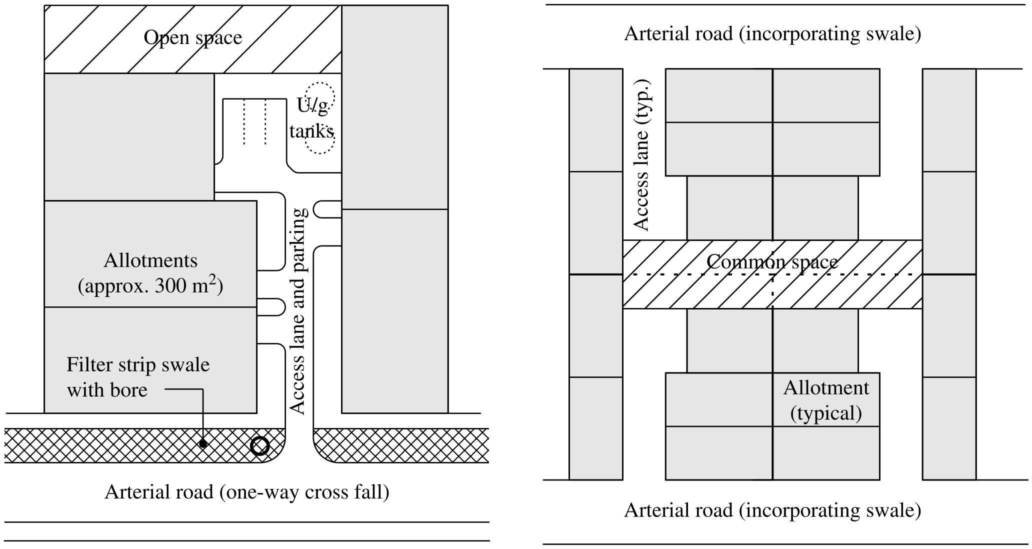

Figure 2 | Reuse model showing a cluster block and a series of linked cluster blocks.

cluster dwellings is piped to the tanks and tank top-up is achieved via a mains water pipe located within the arterial road (not shown in the figure). This mains supply also caters for fire-fighting hence pipe diameters within the cluster can be minimised to that required for water supply only.

Surface runoff from the street, laneway and allotments is treated in a roadside bioretention swale and stored in aquifers (if suitable are present) via recharge bores. Water is recovered from the aquifer for ex-house water uses.

Planning requirements for many Australian cities require the provision of dedicated open space in residential areas for recreational and leisure purposes. In Adelaide this must be a minimum of 12.5% of the development area and where this is not provided a fee is levied on the development enabling purchase of the necessary space elsewhere. The open space area of the model can fulfil such a requirement. Under the proposed model, the wastewater treatment facilities are located in the common/open space precinct and supply irrigation water to this same area, thus minimising transfer pipework.

This mews-type model is an integral unit which forms a building block for developments. By grouping together a number of these blocks, a residential suburb can be created with the open space areas combined to create a common recreational domain. A theoretical 20-unit development is also illustrated in Figure 2.

WATER BALANCE ANALYSIS

A water balance analysis has been undertaken to establish the level of self-sufficiency that might be achieved using the reuse model. A 5 dwelling mews block was analysed using the WaterCress tool (Clark *et al.* 2002) to simulate the in-house and ex-house reuse systems.

WaterCress (Water–Community Resource Evaluation and Simulation System) has been "developed to explore the feasibility of supplying an array of water demands… from an array of water sources" (Clark *et al.* 2002). It is a daily water balance model which can simulate and assess water systems which utilise multiple sources of water, including those generally regarded as being less conventional (e.g. stormwater and wastewater). Nodes are used to represent the elements of the water system (including catchment, demand and storage elements) while links represent the drainage or water supply paths between the nodes.

Table 1 | Areas for a 5 dwelling mews block

Surface type	Area (m^2)
Roof	725
Allotment (ex-house only)	801
Laneway	235
Open space	543
Verge	79
Roadway (half)	181

Roof and surface runoff are dependent on the contributing surface areas and the values used in the water balance analysis are quantified in Table 1. Only half of the arterial road reserve area has been included as, in a larger development, mews could be located on both sides of this road. In such a case the total volume of road runoff would be divided between both clusters. Roof area has been established from a generalised relationship between roof area and allotment size (Barton 2005). The runoff coefficients adopted for each contributing area type are given in Table 2.

In-house and ex-house water demand quantities were based on research into domestic water consumption in Adelaide (Barton 2005). In-house demand of 139 kL/dwelling/annum was adopted with distribution being constant for each day of the year. Ex-house demand for Adelaide averages approximately 136 kL/dwelling/annum, however this applies to an average allotment size somewhat larger than that for the development layout modelled. It has been estimated on the basis of area ratios that an average allotment of 300 m^2 would use about one-third of the ex-house water use of an average Adelaide allotment, hence for this research a conservative estimate of half the Adelaide average ex-house water use (68 kL/dwelling/

Table 2 | Runoff coefficients

Surface type	C
Open space/verge	0.1
Allotment (ex-house)	0.5
Roof	0.9
Roadway/laneway	0.9

annum) was adopted as the ex-house demand. This total ex-house water use was distributed on a month by month basis in accordance with the monthly distribution pattern given by Barton (2005).

A 30 kL tank capacity (i.e. 6 kL per allotment) was adopted for this analysis. For surface runoff it was assumed that this could be stored in a local aquifer, however only that volume of water recharged could be recovered for use.

A daily rainfall record of 97 years (1900–1996 inclusive) was made available by the Australian Bureau of Meteorology. The average annual rainfall for this record (Kent Town) is 535 mm.

Results for average annual runoff and yield, for the modelling period, are shown in Table 3 for the in-house and ex-house supply systems. Yield from roof runoff (i.e. total runoff minus overflow) is 317 kL/annum, which equates to 46% of total in-house demand, while surface runoff exceeded ex-house demand by 25%. Tank losses averaged 14 kL/annum–hence the 30 kL tank capacity was able to capture 95% of available runoff. Under this scenario, stormwater resources would be able to supply about 63% of the total in-house and ex-house water demand for a five dwelling cluster–657 kL/annum of a total demand of 1,035 kL/annum.

MODEL APPLICATION AND COST ANALYSIS

To illustrate the application of the model to a development site and undertake an estimation of the differences in development costs between the conventional and reuse development scenarios, a development site, for which a conventional layout had been designed and costed, was re-designed and costed using the reuse model. Results for the reuse scenario were compared with the conventional scenario.

Table 3 | Water balance analysis results

Supply system	Demand (kL/yr)	Runoff (kL/yr)	Loss (kL/yr)	Yield (kL/yr)
In-house	695	331	14	317
Ex-house	340	425	0	340
Total	1,035	756	14	657

Site description and conventional scenario

The site boundaries and conventional development layout are shown in Figure 3. It comprises a roughly triangular shaped area of approximately 5.4 ha which slopes mildly towards the south-west corner at a grade of around 1%. Soils consist mainly of clays and sandy/loamy clays. An aquifer with an average yield of 4.7 L/s and a water quality of around 830 mg/L TDS is located at 50 m depth.

The conventional development consists of 55 allotments with an average size of 754 m^2. A major thoroughfare divides the development into northern and southern zones and two access roads branch off from this thoroughfare, giving access to the majority of the allotments. One constraint affecting the application of the reuse model to this site was the requirement to retain the central, east-west, thoroughfare to link the development with external roadways.

The reuse scenario

The reuse scenario is illustrated in Figure 4. It consists of eight clusters ranging from five to eight dwellings with an average allotment size of 400 m^2. The total number of allotments (56) was one more than that for the conventional layout however with the reduced allotment size the recreational/common space increased from around 800 m^2 to 21 ha, or almost 40% of the total area. This provided considerable space for wastewater treatment and irrigation.

A roadside swale was sited on the lower side of the main thoroughfare to collect, treat and infiltrate stormwater runoff from the road reserve and the northern (up-hill) half of the development. The pavement width of the main thoroughfare was also reduced. Extra road width is typically allowed to satisfy development requirements for parking space, and this has been provided within each housing cluster instead.

To collect, treat and infiltrate surface runoff from the southern half of the development an infiltration basin, located in the south-western (lowest) corner of the site, has been included in the design layout. This called for some minor additional earthworks to ensure the majority of runoff from the southern sector is captured by the basin.

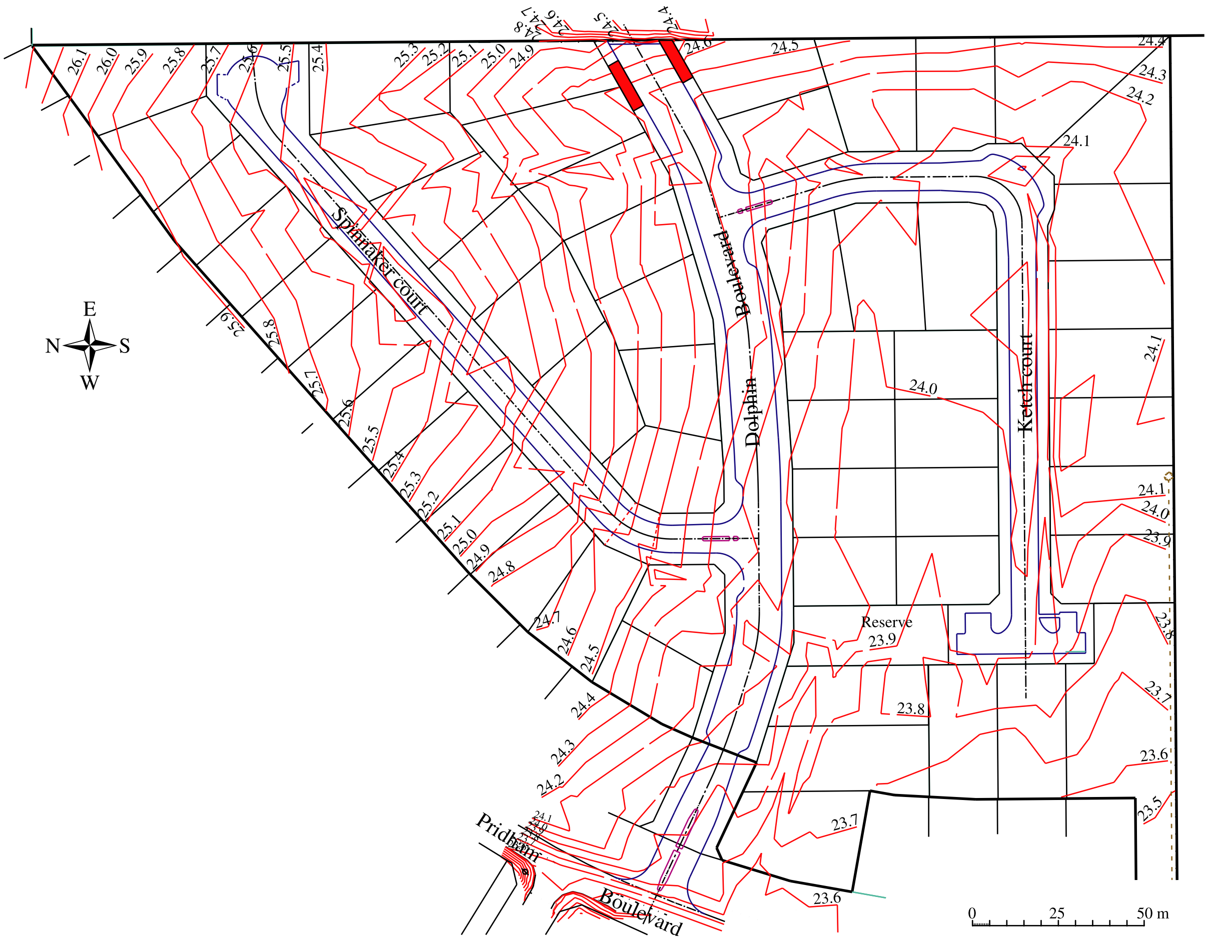

Figure 3 | The conventional development layout.

Infiltration calculations verified that sufficient open space was available to utilise all wastewater from the development for irrigation purposes.

Development costs

Design and costing of the water systems infrastructure–including rainwater tanks, wastewater treatment systems, swale, infiltration basin, pipework and pumps–is detailed in Barton (2005). An all-waste Biolytix system® (Porteous 2005) was costed for treatment of wastewater. Construction estimates for the conventional development were made available by the developer and these were modified to obtain a cost estimate for the reuse development.

Cost estimates for both development scenarios are given in Table 4. These not only include the in-ground construction costs but, additionally, government fees and charges required to be paid by the developer. Fees and charges levied on the conventional development included those associated with connection to external water and sewerage services, and the open space contribution payable where the designated open space does not meet the minimum 12.5% standard. For the conventional development water services charges were particularly hefty due to augmentation fees for both water and sewer. While the reuse development does have connection to the external water supply it was deemed that, as this was for tank top-up only, the connection would not increase peak demand hence augmentation charges were not applicable.

It is evident from Table 4 that while reuse infrastructure increases construction costs this increase has been largely offset by the savings in fees and charges. The reuse scenario

Figure 4 | A development layout based on the reuse model.

has been found to be only slightly (6%) higher in cost compared to the conventional scenario when all development costs are considered.

DISCUSSION

The reuse model potential

The water reuse model presented in this paper provides a method for integrating water cycle management into residential subdivision design. In particular this model exploits the significant amounts of stormwater runoff which is generally of higher quality than wastewater but has typically been omitted from larger scale urban reuse schemes. The modular aspect of the model enables it to be used on a wide range of scales.

Water balance analysis has indicated that, using the model, a significant amount of residential uses can be satisfied by local stormwater resources. It has been found that, for an annual rainfall of around 500 mm/yr, roof runoff alone can satisfy around 40% of an in-house demand of 380 L/day. Surface runoff can potentially satisfy all of an ex-house water demand of around 370 L/day.

The case study has demonstrated how the reuse model can be applied to bring a high level of self-sufficiency to residential development. Smaller individual allotments are a feature of the reuse model with private space being exchanged for more common open space. This is important for the accommodation of the public reuse facilities and local wastewater management. The smaller allotment size fosters water conservation through a reduction in outdoor water use, while the setting aside of more open space can

Table 4 | Development Costs for the conventional and reuse development scenarios (2,004 dollars)

Item	Conventional ($)	Reuse ($)
Construction costs	760,800	1,150,200
Government charges	198,400	3,000
Open space contribution	129,200	0
Total	1,088,400	1,154,200

also facilitate the preservation or reinstatement of native vegetation and habitats which in the past have been sacrificed to urban sprawl and allows the necessary space for water harvesting.

The reuse model maintains aesthetic values while adding to the amenity of the residential domain. Within the concept of sustainable cities there is a need to reduce vehicular travel and promote more environmentally friendly models of transport. The combined common area of the reuse model can also serve as an access corridor between the clusters, encouraging excursions by foot or bicycle.

Under certain site conditions (e.g. for smaller development sites or development around environmentally significant areas) it may not be possible to implement the wastewater management component of the model. In such instances wastewater would need to be piped to regional wastewater treatment facilities. However, as the model concentrates on the residential sector of cities, it can also be viewed as a module of a larger reuse model such as the Weber DOT-NET model. In this case, the stormwater reuse components of the residential reuse model would operate within the Residential component of the DOT-NET model, with the central water treatment plant supplying top-up water to the tanks. The wastewater component could operate as suggested by the residential reuse model but if conditions did not suit, it could feed into the larger reuse scheme supplying industrial and recreational needs further afield.

Importantly the inclusion of reuse into the residential subdivision has potential to impact positively on regional water infrastructure. “Upstream” of the modern urban domain is extensive infrastructure for the capture, treatment and conveyance of an all-purpose water supply; “downstream” are the large pipe networks for the swift conveyance and discharge of stormwater as well as the pipes and facilities for the treatment and disposal of wastewater flows. Reuse can impact significantly on these flows. Continued development progressively increases flow rates, discharge volumes and treatment plant loads, necessitating augmentation of systems infrastructure. The reuse model, however, has the potential to change this trend and pay significant financial dividends by delaying, or even eliminating, the onset of costly upgrade works.

Cost analysis

Analysis of the preliminary costs estimates for the conventional and reuse scenarios shows that the reuse scenario is of similar cost as the conventional scenario when fees and charges are taken into consideration.

It is relevant to point out that these fees and charges may increase as governments are required to address the environmental issues generated by urban development. In Melbourne, Australia, contribution rates for drainage and water quality treatment infrastructure (typically “end of pipe” wetlands) are payable by developers of greenfield sites with the contribution rates based on the total cost incurred by Melbourne Water. Melbourne Water is also pursuing a scheme that would reduce the contribution rate for developments demonstrating compliance with water quality targets using on-site measures (Lloyd *et al.* 2004). As time goes by it can be expected that development “contributions” will accrue, as issues associated with asset replacement and upgrade, and the environment become more pressing.

CONCLUSIONS

This paper takes the “ fit for purpose” concept and applies it in the development of a model aimed at changing current practices with respect to residential development by integrating reuse systems into the design layout while maintaining social values with respect to risk and amenity. In particular it implements reuse of the large quantities of stormwater runoff from the urban domain enabling a significant level of self-sufficiency to be attained.

This residential reuse model provides an approach to the design of residential developments seeking to augment water reuse. It has application to both greenfield and infill development on either a large or small scale and can be incorporated into larger reuse models such as the DOT-NET model.

While application of the model is dependent on site conditions, one case study has shown that the concepts of the model can be used to bring a reasonable level of water self-sufficiency to a residential development with only a slight increase in initial costs. Furthermore it is envisaged that as governments seek to increase development levies to offset the costs of asset replacement and augmentation, and environmental impacts, the economic viability of such developments will only increase.

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