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Centralised urban stormwater harvesting for potable reuse

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ABSTRACT

Urban impervious areas provide a guaranteed source of runoff, especially in cities with high rainfall – this represents a source of water with low sensitivity to unfavourable climate change. Whilst the potential to reuse stormwater has long been recognised, its quality has largely limited usage to non-potable applications requiring the use of a third-pipe network, a prohibitively expensive option in established urban areas. Given recent advances in membrane filtration, this study investigates the potential of harvesting and treating stormwater to a potable standard to enable use of the potable distribution network. A case study based on the Throsby Creek catchment in Newcastle explores the issue. The high seasonally uniform rainfall provides insight into the maximum potential of such an option. Multicriterion optimisation was used to identify Pareto optimal solutions for harvesting, storing and treating stormwater. It is shown that harvesting and treating stormwater from a 13 km^2 catchment can produce yields ranging from 8.5 to 14.2 ML/day at costs ranging from AU$2.60/kL to AU$2.89/kL, which may become viable as the cost of traditional supply continues to grow. However, there are significant social impacts to deal with including alienation of public land for storage and community acceptance of treated stormwater.

Key words | Australia, case study, harvesting, Newcastle, potable, stormwater, reuse

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INTRODUCTION

Recent years of severe drought in many parts of Australia has brought widespread public attention to issues of drought security. While stormwater has traditionally been regarded an encumbrance amongst stormwater management stakeholders, increased demand for water resources is encouraging the recognition of stormwater as an asset.

The Throsby Creek catchment in Newcastle, NSW, Australia receives approximately 1200 mm of annual rainfall. Due to a large percentage of impervious area, much of this rainfall forms runoff which flows into a network of channels before discharging into Newcastle Harbour. Public outcry regarding the perceived 'waste' of Newcastle's stormwater has sparked interest in the potential to harvest and recycle stormwater on a metropolitan scale.

Whilst the potential to reuse stormwater has long been recognised, its substandard quality has often limited usage to non-potable applications. Such use requires the establishment of a third-pipe network for distribution which, in areas of established urban development, is judged to be a prohibitively expensive option. Indeed, pipe construction in dense urban areas can cost up to 2.5 times more than similar works in new developments (Hunter Water Corporation 2003). Treatment of stormwater to a potable standard, however, would allow the use of existing pipe networks for distribution.

The success of the Blackmans Swamp Creek project by Orange City Council has shown that potable reuse is indeed achievable in a low-contaminant catchment using existing ozone and biologically activated carbon treatment facilities (Orange City Council 2009). However, in large cities with heavy past and present industrial activity, dense populations and extensive impervious areas, such treatment is likely to be unsatisfactory in addressing existing and emerging risks of stormwater reuse.

This paper reports on a study into recycling stormwater in the Throsby Creek catchment. With recent advances in

doi: 10.2166/wst.2011.003

membrane water treatment technology, it was judged that potable reuse of stormwater in metropolitan catchments may be increasingly viable. The Throsby Creek catchment presented an ideal setting to investigate the potential of stormwater recycling due to its near uniform high rainfall climate and moderately dense urban development.

The study took a holistic approach to the concept of stormwater harvesting for reuse in the Throsby Creek catchment and is thus broad scoped, entailing catchment modelling, stormwater discharge gauging, water quality analysis, conceptual development and optimisation of components, investigation of treatment options and social, environmental and economic assessment.

CENTRALISED STORMWATER HARVESTING FOR POTABLE REUSE

There are many potential methods and systems for recycling stormwater. Decentralised approaches are commonplace throughout the world, with designers often employing autonomous water sensitive urban design (WSUD) practices in the development of new urban areas and in limited applications for existing developments. At a household level, the quality of harvested rainfall runoff can be controlled by user-maintained and monitored systems.

However, it is much more difficult to control the quality of stormwater harvested by a centralised, large-scale system. Urban runoff carries a range of pollutants including metals, chemicals and organics emanating from a large variety of sources such as roads, waste and industry. For this reason, the reuse potential of urban stormwater has largely been limited to non-potable applications, which require a third-pipe distribution network, typically a prohibitively expensive option in existing urban developments.

In contrast, a centralised harvesting system that provides means of treating stormwater to a potable standard can avoid the need for a third-pipe distribution network by connecting directly into the existing potable distribution network. Figure 1 presents a schematic of this concept.

A centralised stormwater harvesting system for potable reuse requires the following elements:

(i) hydraulic infrastructure to divert flow from the stormwater channel into a retention basin;
(ii) a pump and pipeline to convey harvested water from the retention basin to a main reservoir with sufficient carry-over storage to ensure a reliable supply of water for treatment and distribution;
(iii) a treatment plant to treat water to a potable standard; and
(iv) connection into the existing potable water distribution network

This concept provides the foundation for the Throsby Creek catchment reuse scheme reported in the remainder of this paper.

STORMWATER HARVESTING AND REUSE CONCEPTS IN NEWCASTLE

The study focussed on the capture of runoff from Styx Creek, an arterial branch of the Throsby Creek catchment channel network. Styx Creek flows through urban Newcastle from its origin at Nesbitt Park, Kotara, to its junction with Throsby Creek at Islington. The Throsby Creek catchment is topographically characterised by a relatively flat basin surrounded by hilly terrain to the north, west and south, with Newcastle harbour to the north-east. The creek is predominantly flanked by moderately dense residential developments, with several public parks situated on its banks. The catchment is illustrated in Figure 2.

The Throsby Creek catchment presented several options for configuring the harvesting and reuse components. Four parks, each adjacent to a stormwater channel branch, were identified as practicable locations for the construction of a

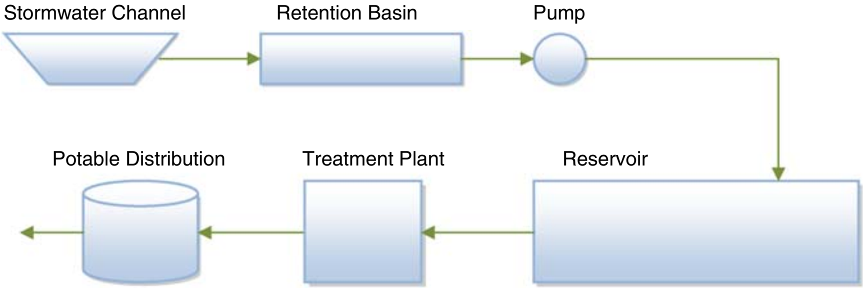

Figure 1 | Schematic of potable stormwater harvesting and reuse system. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

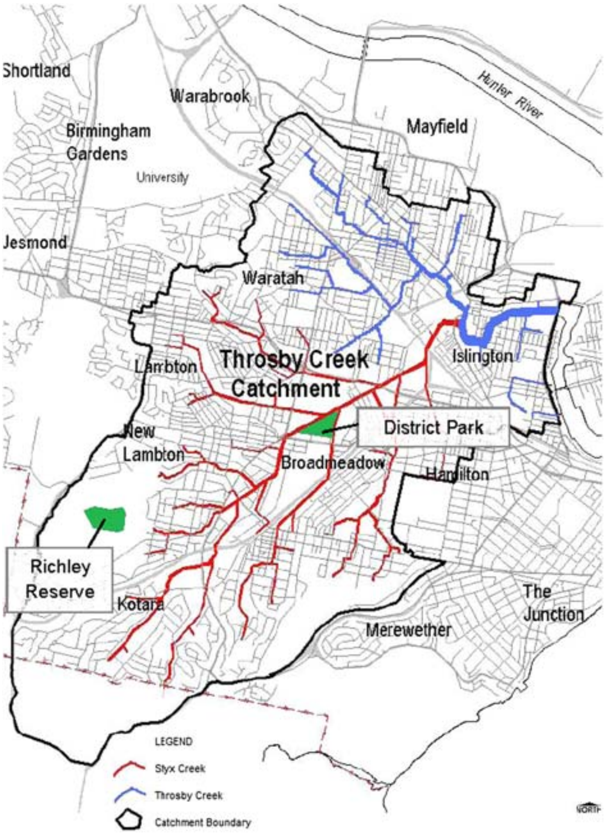

Figure 2 | Throsby Creek catchment. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

detention basin and pumping station based on their location, size and present use. The parks identified were:

(i) Alder Park, New Lambton
(ii) District Park, Broadmeadow
(iii) New Lambton Park, New Lambton
(iv) Waratah Park, Waratah

Further sites were identified for the location of the reservoir. These sites were distinguished in conjunction with the harvesting sites, largely on the basis of their likely capacity and constructability. These locations were:

(i) Richley Reserve, Blackbutt Reserve, New Lambton. This is a popular recreational area located in a large forest reserve. A natural gulley at the head of the recreational area offers an ideal location for a large reservoir.
(ii) Waratah Reservoirs (decommissioned). These reservoirs are presently unused due to damage and would require repair, but would be less costly than building a new reservoir. However, this site has a maximum storage capacity of 180 ML which is substantially smaller than the maximum capacity potentially available at Richley Reserve.

In this paper, discussion is restricted to the most practicable site combination of District Park for diversion and detention and Richley Reserve for main reservoir and treatment.

Rainfall-runoff assessment

Integral to stormwater harvesting on any scale is the quantity of flow through the system. With no physically recorded discharge data available for Styx Creek, it was imperative that discharge through the stormwater channel network be quantified. This was approached using two techniques: a desktop rainfall-runoff model developed using SIMHYD, as well as the establishment of a discharge gauging station to physically measure flows. The desktop study was necessary to provide a preliminary estimate of runoff yield at each potential harvest site. The gauging station will ensure a more realistic parameterisation of the SIMHYD model, but will require several years of operation to provide sufficient data.

SIMHYD is a lumped conceptual daily rainfall-runoff model that uses daily precipitation and potential evapotranspiration data in simulating runoff for ungauged catchments (Chiew & Siriwardena 2005). The SIMHYD model of the Throsby Creek catchment determined that of the possible locations, the channel section adjacent to District Park produced the largest average discharge at approximately 9700 ML/yr from a 13 km^2 catchment. High discharges were expected as this section exhibits the largest tributary area of the four assessed locations. A 140-year historic daily rainfall record was routed through SIMHYD to provide a long time series of daily runoff at District Park.

The development of a gauging station sought to establish a means of automatically recording discharge data in Styx Creek. Upon identification of a step critical depth control in the channel bed adjacent to District Park, a stage-discharge based gauge was designed and installed. Figure 3 illustrates the step control. Using pressure sensors embedded in the channel floor, the continuous measurement of stage, discharge and modular limit over the section was initiated. Data recorded by the gauging station will be used to calibrate the SIMHYD model for future studies. Figure 4 illustrates a storm event from 3 to 8 September 2008.

Stormwater quality assessment

The gauging station was supervised by a Datataker DT50 data logger which provided the capability to activate a slave ISCO

Figure 3 | Styx Creek adjacent to District Park. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

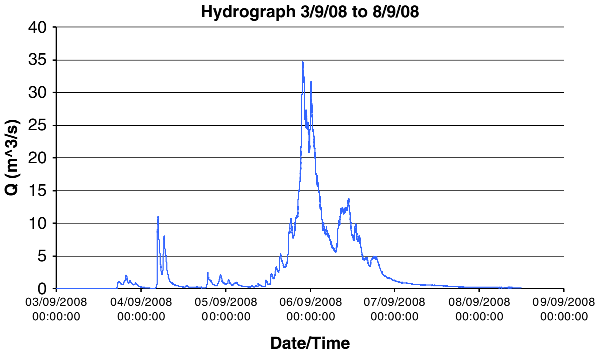

Figure 4 | District Park hydrograph 3–8 September 2008. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

6700 water quality sampler. A storm event-based sampling schedule was developed to draw samples at given increments of discharge, thus presenting a measure of water quality distributed over the storm event hydrograph. Water quality samples were analysed at the NATA accredited Hunter Water Australia Laboratories to determine appropriate treatment options.

The results of the raw stormwater quality analysis were compared with limits set out by the Australian Drinking Water Guidelines (ADWG). Samples were tested for 103 different pollutants consisting of chemical and physical parameters, metals, pesticides and organics (including trihalomethane and total petroleum hydrocarbons). Table 1 highlights the pollutant levels which exceeded ADWG limits over two storm events in August and September 2008.

Of the 103 raw stormwater parameters analysed for each storm event, only turbidity and a selection of metals exceeded ADWG limits. With a limited water quality monitoring history for the catchment, water quality results were compared with established pollutant ranges for urban catchments (Wong 2006), yielding similar results. It should be noted that the established pollutant ranges for urban catchments do not thoroughly investigate levels of organics, pesticides or emerging contaminants such as pharmaceutical and personal care products (PPCPs).

Stormwater treatment options

Membrane technologies have evolved substantially over the last two decades from a specialty technology with applications in beverage filtration and industrial waste treatment to a mainstream water treatment technology. A review of membrane treatment technologies (and other technologies used in conjunction with membrane treatment) identified microfiltration (MF) / ultrafiltration (UF), reverse osmosis (RO) and advan-

Table 1 | Summary of Styx Creek ADWG Exceedances

		ADWG Levels				
Analysis	**Units**	**Health**	**Aesthetic**	**Minimum**	**Average**	**Maximum**
Turbidity	NTU	na	5	34	139.3	250
Aluminium	mg/L	na	0.2	0.1	1.2	4.4
Arsenic	μg/L	7	na	1	4	8.9
Cadmium	μg/L	2	na	1	9	25
Iron	μg/L	na	300	70	3899	17400
Lead	μg/L	10	na	1	49	129
Manganese	μg/L	500	100	18	250	810
Nickel	μg/L	20	na	5	15	25

Red font indicates values that exceed ADWG levels.
na – No ADWG level available.

ced oxidation (AO) as three primary processes for effective treatment of stormwater based on the results obtained from Styx Creek.

The ability of MF and UF membranes to remove particles, turbidity and microorganisms is well established and is a key reason for steady growth in mainstream employment of these systems. RO membranes are capable of removing the majority of dissolved organic matter (DOM), while AO is a destructive water treatment technology that transforms biotoxic substances into water and carbon dioxide or harmless by-products (Rivas *et al.* 2008). Furthermore, Snyder *et al.* (2007) demonstrate that membrane technology "can be highly effective for the removal of emerging contaminants" including endocrine disrupting compounds (EDCs) and PPCPs. While wastewater is the major source of these emerging contaminants, stormwater is subject to contamination by their presence in "surface waters, sediments, groundwater and even drinking water" (Liu *et al.* in press) as well as wastewater cross-contamination. Despite the Styx Creek analysis presenting no hazardous levels of pesticides or organics, the treatment system was designed with the intent to remove these pollutants (including emerging contaminants) if present in the stormwater.

MF and UF are particularly suited to stormwater harvesting applications as they are tolerant of variable feedwater quality and are thus effective in improving the feedwater quality for reliable RO operation. A pressurised MF/UF membrane configuration would further provide residual pressure required for RO pre-treatment (Natural Resource Management Ministerial Council 2008; Siemens Water Technologies Corporation 2007).

An optimal treatment configuration for stormwater harvested from Styx Creek was based on an achievable treatment demand of 10 ML/day. The system comprised the following elements:

(i) Primary Treatment – Occurring at the harvest site, coarse screening and grit removal is performed to remove large suspended solids from the water for landfill disposal. Natural processes such as sedimentation, biological uptake of soluble pollutants, chemical absorption and UV disinfection would occur in both the detention basin and the reservoir.

(ii) Fine Screening – A manufacturer requirement for MF and UF membrane processes, this step for further removal of suspended solids <0.9 mm in diameter is integrated into the pumping of feedwater between the reservoir and treatment plant.

(iii) UF Membrane – Preparation of feedwater for RO purification. Monochloramine is added prior to filtration to reduce membrane bio-fouling.

(iv) RO Membrane – Feedwater pumped at increased pressure through RO membrane system. To prevent scaling and membrane fouling, pH reduction and antiscalent additives are dosed as pre-treatments.

(v) AO – The final treatment process whereby hydrogen peroxide and UV destroys trace contaminants by breaking their molecular bonds. The treated water is dosed with caustic acid post AO to stabilise pH in accordance with the ADWGs. Free chlorine dosing provides residual disinfection.

It is necessary to consider appropriate disposal of the treatment process rejection stream. Its high toxicity would prohibit disposal into natural waters (Snyder *et al.* 2007) and thus it is recommended that further research be conducted into disposal via the existing wastewater system for conventional treatment. With the adopted daily treatment of 10ML/day, it is estimated from UF and RO recovery rates that a maximum of 3.2 ML/day would be rejected and require disposal. This is a conservative estimation as this does not consider the recycling of reject through the treatment process using techniques such as sludge settling and supernatant return.

A conceptual cost estimate was compiled for the aforementioned treatment configuration based on capital, operational and maintenance costs. Table 2 presents a summary of these costs for a treatment plant with a 10 ML/day input, including a 30% contingency to ensure the costs remained conservative.

Multi-criterion optimisation of system components

The design of the Throsby Creek catchment reuse scheme required the specification of five key variables which are summarised in Table 3 along with their ranges. A computer simulation model of the Styx reuse system was developed using the 140 years of daily runoff at District Park as the input. A multi-criterion genetic algorithm (Jefferson *et al.*

Table 2 | Treatment costs for plant with 10 ML/day capacity and 30 year life.

Description	Cost
Total Capital Costs	AU$24,200,000
Yearly Operating Costs	AU$2,000,000
Life Cycle Costs @ 7%	AU$52,200,000
Estimated Water Cost	AU$0.76/kL

Table 3 | Key optimisation variables.

No.	Name	Description	Range
1	Retention	Storage capacity of the District Park retention basin	0 to 100 ML
2	Pump	Capacity of the pump to transfer water to the main reservoir	0 to 200 ML/day
3	Pipe size	Diameter of the transfer pipe	0.2 to 1.7 m
4	Reservoir	Capacity of the reservoir at Richley Reserve	0 to 1000 ML
5	Treatment	Maximum treatment capacity	0 to 20 ML/day

2005) was used to find the Pareto optimal solutions involving the five variables for the following objectives:

(i) Minimise present worth of the capital and operating costs expressed as AU$/kL potable water delivered to the consumer. This cost includes all capital and operating costs for delivering water to the distribution system plus an additional AU$0.90/kL for using the distribution system to deliver water to the consumer.
(ii) Maximise the average daily yield of potable water delivered to the distribution system (ML/day).
(iii) Minimise the size of storage to curtail the impact on amenity at Richley Reserve, a popular recreational reserve.

Reliability of supply was not included in the optimisation. This is because the reuse scheme provides a complimentary augmentation to the existing mains water supply, rather than a stand-alone water source. The primary benefit of the Styx Creek scheme is to reduce the seasonal demand on the mains water system. This increases the overall security of the regional water supply by slowing the drawdown rate of the large centralised reservoirs, thereby reducing the risk of restrictions and severe shortages.

Figure 5 presents the Pareto surface for the three criteria. This surface allows a decision maker to make trade-offs between the three competing criteria knowing that all dominated solutions have been eliminated by the genetic algorithm search. This surface is best visualised by real time rotation of the axes. To assist in the interpretations of the results, two-dimensional projections of the Pareto surface are presented in Figures 6 and 7.

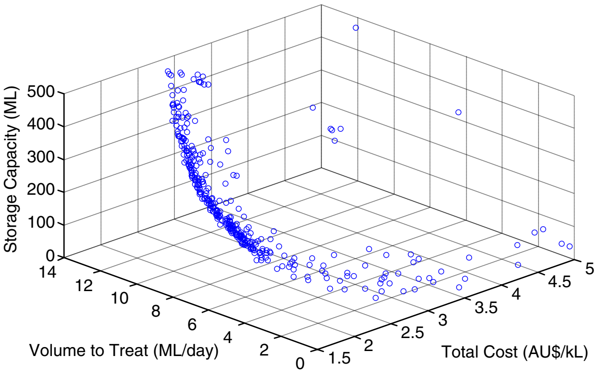

Figure 5 | Throsby Creek Catchment reuse scheme Pareto surface. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

Figure 6 shows the trade-off between cost and yield. It can be seen that the volume to treat-cost tradeoff is very steep: At the lower end there exists a solution which for AU$2.60/kL produces a yield of 8.5 ML/day. For a relatively small increase in unit cost to AU$2.82/kL the yield can be

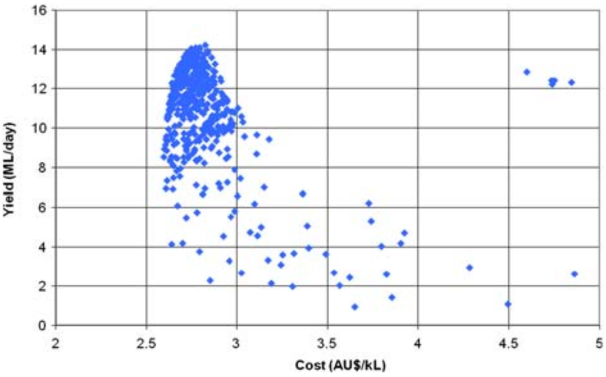

Figure 6 | Volume to treat vs. Cost trade-off between Pareto optimal solutions. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

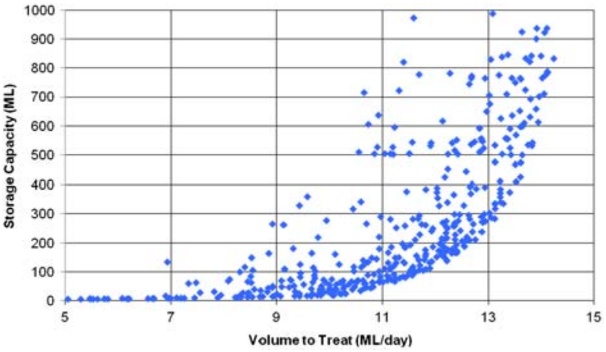

Figure 7 | Volume to treat vs. storage capacity trade-off between Pareto optimal solutions. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

Table 4 | Three Pareto optimal solutions

				Variable				
Solution	Storage capacity (ML)	Volume to treat (ML/day)	Total cost (AU$/kL)	Retention (ML)	Pump (ML/day)	Pipe size (m)	Reservoir (ML)	Treatment (ML/day)
1	18.7	9.63	2.89	99	51	0.80	18.7	17.0
2	221.0	10.9	2.67	99	95	0.94	220	13.4
3	744.9	12.6	2.68	96	115	0.73	745	14.4

increased to 14.2 ML/day. However, to achieve this large jump in yield it is necessary to substantially increase the storage capacity to retain the large but intermittent flows down Styx Creek. Figure 7 clearly shows the trade-off between volume to treat and storage capacity – to realize a volume to treat of over 14 ML/day would require a storage in excess of 600 ML, a size that would represent a very large impact on the amenity of the existing recreational area and on residents who live downstream.

Further insight can be derived by considering the three distinctly different Pareto solutions summarised in Table 4. The solutions represent low, high and very high impacts on the recreational amenity of Richley Reserve and on downstream residents. All three solutions opt for the largest allowable retention basin storage at District Park with similar pump and pipe sizes. The principal differences arise in the size of the treatment plant and storage capacity, and are as follows:

(i) Solution 1 opts for a large treatment plant with about one day of storage at Richely Reserve. The primary storage is thus District Park retention basin.
(ii) Solution 2 opts for about 16 days of storage capacity at Richley Reserve. This supports a smaller treatment plant than Solution 1, while achieving a similar volume to treat.
(iii) Solution 3 obtains additional volume to treat by opting for over 50 days of storage capacity at Richley Reserve. This enables storage of bigger volumes in the larger runoff events.

It is of interest to compare the cost of water from the reuse scheme against the mains water price set by the regulator, the Independent Pricing and Regulatory Tribunal of NSW (IPART). Table 5 lists the draft price proposals for Hunter Water Corporation residential customers over the next five years. One can see that the mains water price remains well under the reuse cost even after price escalates to AU$1.86/kL by 2012.

Of interest is the efficiency of the reuse scheme. For a 13 km^2 catchment, yields of 8.5 to 14.2 ML/day translate into annual runoff of 239 to 400 mm. This represents harvesting between 20 and 33% of average annual rainfall. Although Newcastle has a uniform rainfall regime, the depth of rainfall in individual events is highly variable. A drier climate with less variability in event rainfall may produce similar yields. Indeed this was confirmed using Melbourne rainfall as an input to Styx Creek. Despite the annual average rainfall for Melbourne being about half of Newcastle, the yield was very similar.

Social acceptance

The intermittent nature of runoff requires considerable storage in a stormwater reuse scheme to ensure an adequate yield from the treatment plant. Locating adequate storage opportunities in an established urban community is problematic. As demonstrated for Styx Creek, such opportunities are largely restricted to publicly owned land which in most cases would be utilised for some recreational purpose. In the case of Richley Reserve, the construction of a dam that would reduce the area available for recreational pursuits and pose a risk of dam failure to downstream residents represents a major social issue that may transcend cost and yield issues.

Moreover, potable reuse of stormwater requires acceptance by stakeholders. While there is recognised public support for stormwater reuse in non-potable applications

Table 5 | IPART Draft Price of Water for HWC (taken from IPART 2009, p. 175)

Financial year	Price (AU$/kL)
08/09	1.27
09/10	1.51
10/11	1.62
11/12	1.74
12/13	1.86

(Hunter Water Corporation, 2008), there has been little investigation into the acceptability of potable stormwater reuse. There has, however, been substantial research conducted into social acceptance of recycled wastewater, in which proposals have been met with considerable opposition (Hurlimann 2008). While surveys into the use of recycled water initially show strong community support, this support will usually decline when people are faced with an actual project proposal (Hunter Water Corporation, 2008).

However, intense drought throughout NSW in recent years accompanied by severe water restrictions has brought about increased public engagement with issues of water scarcity and security. Under these conditions, Australians have shown less resistance to recycled water (Dolnicar & Schäfer 2009). Nonetheless, causes for potential public opposition to a stormwater recycling scheme in Newcastle would most likely include:

(i) Concern for public health. With minimal proven, existing implementation of centralised stormwater recycling schemes, a proposal would be viewed as experimental and would encounter scepticism (Dolnicar & Schäfer 2009; Noble 2005).

(ii) Economic impact. Water users would be wary of increases in the cost of water – specifically if and/or how the cost of the project is passed on to the consumer. Conversely, support will increase if a scheme can produce economic benefits for the consumer.

(iii) Environmental impact and social value of land. The Styx Creek study proposes the flooding of popular recreation areas and wildlife reserves to accommodate infrastructure. These areas are of significant social and environmental value to the community, reclamation of which would encounter substantial public opposition.

CONCLUSIONS

This study has investigated the viability of a potable stormwater reuse scheme in an established urban catchment located in the Throsby Creek catchment, Newcastle. The study was motivated by the concern that non-potable stormwater reuse in established urban areas would require a third-pipe network which would be economically unviable. It was shown that optimising a reuse scheme which harvested water at District Park (a 13 km^2 catchment) and stored and treated water at Richley Reserve could produce yields ranging from 8.5 to 14.2 ML/day at costs ranging from AU$2.60/kL to AU$2.82/kL. Though these costs are higher than mains water charges (AU$1.27/kL in 2009 and up to AU$1.86/kL in 2012), they are, nonetheless, comparable and may become attractive as urban communities invest in more expensive headworks supply options to cater for population growth and increased drought security.

It is important to appreciate that economic and technical considerations only address part of the potable stormwater reuse option. While potable stormwater reuse reduces the urban ecological footprint, it can produce a number of direct and significant social impacts which may transcend cost and yield considerations. Locating sites for harvesting and storage in an established urban area is problematic and likely to be restricted to publicly owned land which, in most cases, would be utilised for recreational purposes. Moreover, gaining community acceptance to drink treated stormwater remains a hurdle. In the case of the Throsby Creek catchment reuse scheme, the storage option involving the decommissioned Waratah Reservoirs (with 180 ML capacity) avoids the confiscation of recreational amenity and warrants further investigation.

The Styx Creek case demonstrates the potential of potable stormwater reuse with significant yields and costs that may, in the not-too-distant future, be competitive with traditional headworks options. Perhaps the biggest issue is finding suitable sites for harvesting and storage in established urban communities. If provision for stormwater reuse is incorporated into strategic urban planning there is a real opportunity to reduce the urban ecological footprint.

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