Enabling residential hybrid water systems through a water credit–debit system

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ABSTRACT

Smart metering and data analytics enable the implementation of a range of on-site infrastructures for energy, water and waste management to demonstrate the interconnected infrastructure of future smart cities. A research project in Western Australia is integrating smart metering technology, household participation and data analytics. An improved understanding of hybrid water systems at residential scale, as socially accepted solutions to promote water efficiency and economic savings, within the traditional centralized urban water network is achieved. An integrated water model and a system of water credits and debits are developed and tested on a case study for which 10-minute logged water consumption data of its hybrid water system are available for 1 year. The model is shown to provide a full characterization of the relationship between the household and the water resources, thus assisting with improved urban water management which promotes the rollout of decentralized hybrid water systems whilst accounting for the impacts on the aquifer as an ecosystem service provider.

Key words | credits/debits, greywater, groundwater, rainwater, smart meters, water balance

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INTRODUCTION

Hybrid water systems, advanced metering technology and data analytics across a distributed water ledger are emerging as a new integrated approach to smart urban water management. In a similar manner to the phenomenon of rooftop solar photovoltaic systems becoming a popular alternative power supply in urban areas, rainwater tanks, greywater reuse and garden bores have become popular alternative water systems in many cities. When integrated with centralized water networks, these decentralized water systems are commonly referred to as distributed or hybrid water supply systems (Sharma *et al.* 2013; Sapkota *et al.* 2014). The complete hybrid water system for residential buildings is connected to the mains water system and includes additional water sources of rainwater, groundwater and greywater, at the single lot or precinct scale (Anda 2017). Several studies have demonstrated the capability of hybrid water systems to reduce reliance on mains water while simultaneously using less energy (Daigger & Crawford 2007; Stephan & Stephan 2017). Byrne *et al.* (2007) developed and built a Mains Water Neutral (MWN) model by integrating rainwater harvesting, greywater reuse and a groundwater bore (Byrne 2016).

Besides the need for stronger financial incentives, (i.e., water tariffs that better reflect the value of different water streams, awareness campaigns and media coverage promoting water conservation) the installation of hybrid technologies has a strong effect on residential water demand (Hurlimann & Dolnicar 2012; Ferguson *et al.*

doi: 10.2166/ws.2019.093

2013). A metered, seasonal and demand-driven water price that encourages local water harvesting and conservation measures can enable a more sustainable hybrid water supply system (Stephan & Stephan 2017).

Hybrid water systems require smart water meters for a thorough understanding of the system to develop novel concepts such as water credits–debits and water trading. The rapid advancement in water meter technology and wireless communications has allowed a paradigm shift in quantifying water flows within residential properties. The advent of smart ultrasonic meters has enabled the simplification and reduction of costs associated with real-time water flow monitoring (Water Group 2018). The latest generation of smart meters incorporates built-in ultrasonic flow-measuring capability with wireless data transmission embedded within the meter itself (Winkler 2017).

In Western Australia, the widespread use of hybrid water systems in the form of rainwater tanks, groundwater bores and greywater diversion systems installed at lot-scale is changing the relationship of the water consumer to the three water infrastructures (i.e., water supply network, sewerage network, storm water drainage network). Besides the man-made infrastructures, the shallow aquifer constitutes a natural system that has been exploited by Western Australian residents for many decades and is neither licensed, metered nor charged for by the water utility. Groundwater in the shallow aquifer is accessed by private bores and used for irrigation on private lawns and gardens.

Through a combination of hybrid water systems, advanced metering technology and data analytics, we have developed and tested a water model at household scale where the new hybrid water system is integrated with the centralized water network. The household-scale water balance which quantifies the volume of each water stream represents the first step to identify mains water savings, reduced discharge to sewerage, discharge to storm water drainage, and abstraction/discharge to the aquifer. The objective of this paper is to develop a water model where the relationship between the water user and the hybrid water system is quantified through a water balance and a system of water credits and debits. The water modelling framework explained in the paper is tested on a case study in Perth (Western Australia) for which 10-minute logged water data are available for 1 year.

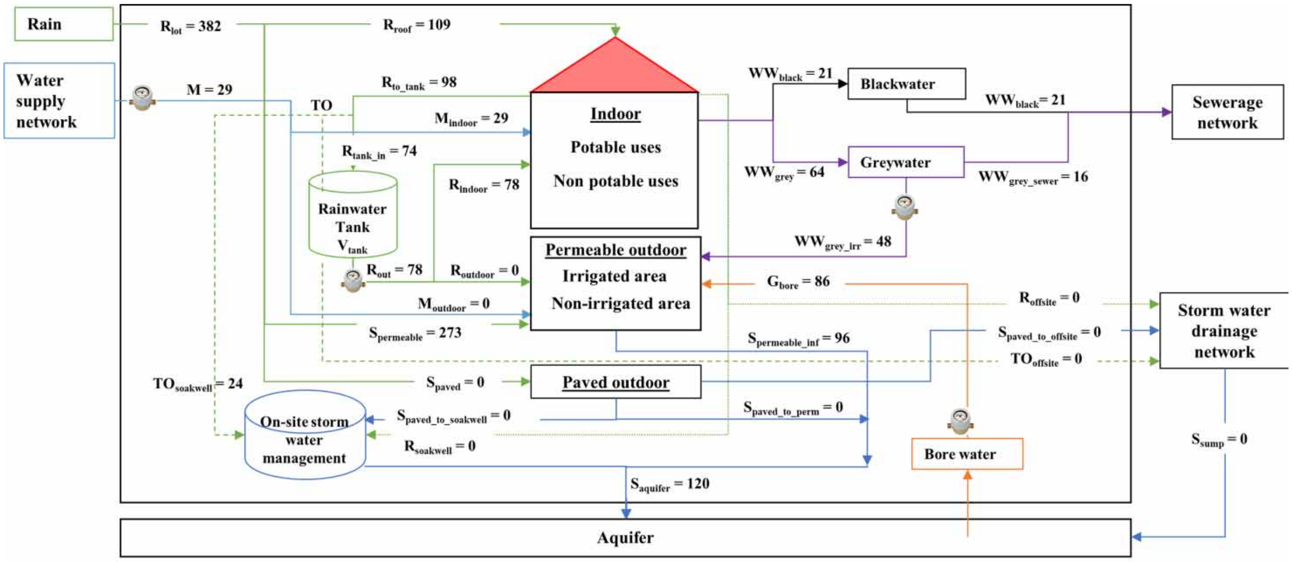
MATERIALS AND METHODS

Case study

The case study analyzed in this paper refers to a three-bedroom, two-bathroom independent dwelling, occupied by a family of two adults and two children (a three-person equivalent is considered to calculate per capita water volumes). The site is located on a 700 m^2 block in Hilton, a suburb of Perth, the state capital city (Western Australia, Figure S1 in the Supplementary Material, available with the online version of this paper). A rainwater tank, groundwater bore and greywater system have been installed at the site and monitored for the entire year of 2015, gathering water flow data every 10 minutes. A schematic diagram of the site and its monitored water flows is shown in Figure 1. Mains water usage has also been monitored every 10 minutes for the entire year of 2015 (Figure 1). Further information on the study area (e.g., location, rainfall and temperature) is specified in the Supplementary Material.

The 18 kl rainwater tank collects the rain falling on the entire roof (catchment area of 200 m^2; Byrne 2016) and is used for indoor potable and non-potable uses after double filtration and UV disinfection installed on the tank outlet. A private groundwater bore is installed on the property to irrigate the 80 m^2 garden. Greywater is collected on-site from all indoor fixtures except the kitchen sink, dishwasher and toilet flushing (Byrne 2016). A greywater diversion device allows the reuse of greywater for garden irrigation, for a total greywater-serviced area of 40 m^2. The combined use of both groundwater and greywater is enough to provide outdoor irrigation, thus no rain or mains water is needed for outdoor uses (Byrne 2016).

The data presented hereafter for mains, rain and groundwater were logged by water flow meters (see Supplementary Material for details) from 1 January to 31 December 2015 at 10-minute intervals. Due to frequent filter clogging, greywater volumes are not available at 10-minute intervals and a daily average greywater volume of 175 l/d was determined from a sampling period of 84 days spanning 1 October to 24 December 2015 (Byrne 2016). Regular cleaning of the meter pre-filter was necessary during this period to minimize inaccuracies resulting from clogging. To estimate the annual amount of greywater used



M	Mains water supply	Spermeable	Storm water on outdoor permeable area	Rout	Rainwater exiting tank		
Mindoor	Mains water used indoor	Spermeable_inf	Storm water on permeable and infiltrated to aquifer	Rindoor	Rainwater used indoor		
Moutdoor	Mains water used outdoor	Spaved	Storm water on outdoor paved area	Routdoor	Rainwater used outdoor	Gbore	Groundwater extracted from bore
Rlot	Rainfall on total lot area	Spaved_to_perm	Storm water on paved areas drained to garden	TO	Tank overflow	WWblack	Blackwater to sewer
Rroof	Rainfall on roof area	Spaved_to_soakwell	Storm water on paved areas sent to soakwell	TOsoakwell	Tank overflow to soakwell	WWgrey	Greywater
Rto_tank	Rainfall to tank	Spaved_to_offsite	Storm water on paved areas sent to offsite runoff	TOoffsite	Tank overflow to offsite runoff	WWgrey_irr	Greywater to irrigation
Rtank_in	Rainwater entering tank	Saquifer	Storm water to on-site aquifer recharge	Roffsite	Rainwater sent to offsite runoff		
Vtank	Rainwater tank volume	Ssump	Storm water to offsite aquifer recharge	Rsoakwell	Rainfall drained to on-site soakwell	WWgrey_sewer	Greywater to sewer

Figure 1 | Schematic diagram of a hybrid water system and annual water balance at the household scale. Symbol (meter) indicates where the smart-meters are installed. Values are expressed in kl and represent the water balance for the entire year 2015.

for irrigation, the 175 l/d daily average is extrapolated over 9 months as no irrigation occurs during the winter months (June to August).

Water balance of a residential hybrid water system

Where both centralized and hybrid water systems are installed, the water balance at the household scale can be complicated due to the several water inputs and outputs to account for. Figure 1 shows a schematic representation of all possible water streams where a rainwater tank, groundwater bore and greywater system are connected along with mains water supply, sewerage, storm water drainage network, and the shallow aquifer.

A water balance was calculated at the study site for the year 2015 following the equations in Table 1 and the assumptions of Table S1 (Supplementary Material, available online). The water balance aims at quantifying all the streams highlighted in Figure 1.

The calculation of storm water flows (identified hereafter by the letters R and S, Table 1) is proportional to the rain falling on roof (R variables, Table 1) and outdoor spaces (S variables, Table 1) and respective areas. Due to specific criteria related to the design of the building (refer to Byrne (2016) and Table S1, Supplementary Material), the following streams in Figure 1 and Table 1 can be set to zero:

- $S_{paved\_to\_perm}$, $S_{paved\_to\_soakwell}$, $S_{paved\_to\_offsite}$ are considered null at the study site because the whole outdoor area is fully permeable – no paved outdoor surfaces (Table S1);
- $R_{soakwell}$ and $R_{offsite}$ are null at the study site because the rain falling on the entire roof is harvested in the rainwater tank (Table S1).

Roof losses, evaporation, evapotranspiration and aquifer infiltration coefficients are applied to the equations in Table 1 through the coefficients η_{roof}, F_{inf} and F_{inf_paved} to

Table 1 | Summary of metered data and water balance equations

Variable	Variable description	Formula (units in kl)
M	Mains water connection	metered data are aggregated at daily intervals
R_{out}	Rainwater tank outlet	metered data are aggregated at daily intervals
R_{indoor}	Rainwater indoor use	equal to R_{out}
$R_{outdoor}$	Rainwater outdoor use	0 (Byrne 2016)
M_{indoor}	Mains water indoor use	equal to M
$M_{outdoor}$	Mains water outdoor use	0 (Byrne 2016)
G_{bore}	Groundwater extracted by bore	metered data are aggregated at daily intervals
WW_{grey}	Greywater	175 l/d, value extrapolated from data measured from 1 Oct to 24 Dec 2015
WW_{grey_irr}	Greywater for irrigation – during irrigation months	equal to WW_{grey}, assumed constant over 9 months of irrigation
WW_{grey_sewer}	Greywater to sewerage – during winter months	equal to WW_{grey}, assumed constant over 3 months of no irrigation (winter)
WW_{total}	Wastewater generation	$\frac{WW_{grey}}{F_{grey}(\%)}$
WW_{black}	Blackwater generation	$WW_{total} - WW_{grey}$
R_{lot}	Total rainfall on the property	$\frac{R(\text{mm})}{1{,}000} \times A_{lot}(\text{m}^2)$
R_{roof}	Total rainfall on the roof	$\frac{R(\text{mm})}{1{,}000} \times A_{roof}(\text{m}^2)$
R_{to_tank}	Rainwater sent to tank	$\frac{R(\text{mm})}{1{,}000} \times A_{\text{roof to tank}}(\text{m}^2) \times \frac{\eta_{roof}(\%)}{100}$
$R_{soakwell}$	Rainwater sent to soakwell	$\frac{R(\text{mm})}{1{,}000} \times A_{\text{roof to soakwell}}(\text{m}^2) \times \frac{\eta_{roof}(\%)}{100}$
$R_{offsite}$	Rainwater sent to off-site runoff	$\frac{R(\text{mm})}{1{,}000} \times A_{\text{roof to offsite}}(\text{m}^2) \times \frac{\eta_{roof}(\%)}{100}$
$S_{permeable}$	Storm water falling on permeable areas	$\frac{R(\text{mm})}{1{,}000} \times A_{perm\_outdoor}(\text{m}^2)$
$S_{permeable\_inf}$	Storm water falling on permeable areas and infiltrated to aquifer	$S_{permeable} \times \frac{F_{inf}(\%)}{100}$
S_{paved}	Storm water falling on paved outdoor areas	$\frac{R(\text{mm})}{1{,}000} \times A_{paved}(\text{m}^2)$
$S_{paved\_to\_perm}$	Storm water falling on paved area, directed to permeable areas and infiltrated to aquifer	$\frac{R(\text{mm})}{1{,}000} \times A_{paved\_garden}(\text{m}^2) \times \frac{F_{inf}(\%)}{100}$
$S_{paved\_to\_soakwell}$	Storm water falling on paved area, directed to soakwell and infiltrated to aquifer	$\frac{R(\text{mm})}{1{,}000} \times A_{paved\_soakwell}(\text{m}^2)$
$S_{paved\_to\_offsite}$	Storm water falling on paved area, directed to off-site storm water drainage	$\frac{R(\text{mm})}{1{,}000} \times A_{paved\_offsite}(\text{m}^2)$
$S_{aquifer}$	Storm water to on-site aquifer recharge	$S_{permeable\_inf} + TO_{soakwell} + R_{soakwell} + S_{paved\_to\_soakwell} + S_{paved\_to\_perm}$
S_{sump}	Storm water to off-site aquifer recharge	$(R_{offsite} + TO_{offsite} + S_{paved\_to\_offsite}) \times \frac{F_{inf\_paved}(\%)}{100}$

evaluate the amount of rainfall harvested in the rainwater tank and the amount of storm water reaching the shallow aquifer for recharge (Table 1). The values of these coefficients are related to regional characteristics and determined in previous studies (refer to Table S1, Supplementary Material).

Table 2 | Definition of the system of debits and credits

	Credit towards				Debit towards			
	Water supply network	Sewerage network	Storm water drainage network	Aquifer	Water supply network	Sewerage network	Storm water drainage network	Aquifer
Water source	R_{out} G_{bore} WW_{grey_irr}	WW_{grey_irr}	R_{tank_in} $TO_{soakwell}$ $S_{paved\_to\_soakwell}$ $S_{paved\_to\_perm}$ $R_{soakwell}$	$S_{aquifer}$ S_{sump}	M_{indoor} $M_{outdoor}$	WW_{grey_sewer} WW_{black}	$S_{paved\_to\_offsite}$ $R_{offsite}$ $TO_{offsite}$	G_{bore} R_{tank_in}

The rainwater tank requires a storage-tank model (Imteaz *et al.* 2011) defined as (Equation (1)):

$$V_{tank}(t) = V_{tank}(t-1) + R_{tank\_in}(t) - R_{out}(t) \quad (1)$$

where t is the time step used in the water balance (i.e., daily), V_{tank} is the volume in the rainwater tank, R_{tank_in} is the rainwater entering the tank every day and R_{out} is the measured volume of rainwater leaving the tank and used indoors ($R_{out} = R_{indoor}$, Figure 1 and Table 1). R_{tank_in} is defined as (Equation (2)):

$$R_{tank\_in}(t) = R_{to\_tank}(t) - TO(t) \quad (2)$$

where R_{to_tank} is defined in Table 1 and TO is the tank overflow calculated at each daily step t according to (Equation (3)):

$$TO(t) = \begin{cases} 0 \ if \ V_{max} - V_{tank}(t-1) \geq R_{to\_tank}(t) - R_{out}(t) \\ (R_{to\_tank}(t) - R_{out}(t)) - (V_{max} - V_{tank}(t-1)) \ if \ V_{max} - V_{tank}(t-1) < R_{to\_tank}(t) - R_{out}(t) \end{cases} \quad (3)$$

where V_{max} is the rainwater tank maximum volume at the study site (Table S1).

As specified in Byrne (2016), the overflow of the rainwater tank is directed to an on-site soakwell and fully contributes to aquifer recharge ($TO = TO_{soakwell}$, Table 1).

Credit–debit system

To account for the impact of each water source on the water infrastructure, a new system of volumetric credits and debits is defined (Table 2). The concept of water credits towards the water supply and sewerage networks refers to the saved volumes of mains water and reduced discharge to sewerage following the adoption of hybrid water systems. The water sources that contribute to a credit towards the water supply network are rainwater tank output (R_{out}), extracted groundwater (G_{bore}) and greywater used for irrigation (WW_{grey_irr}) (Table 2): they constitute a credit towards the water supply network as mains water would have been needed if a hybrid water system was not installed at the site. The water source that contributes to a credit towards the sewerage network is the WW_{grey_irr} as it reduces the amount of discharged sewerage thus avoiding downstream pumping, treatment and, in the case of Perth, pumping to ocean outfall. Water credits are accrued towards the storm water drainage network whenever reduced volumes of storm water are drained off-site as a consequence of rainwater harvesting and on-site storm water management (e.g., soakwells). In the absence of both rainwater tanks and on-site storm water management, no credit is developed towards the storm water drainage due to the entire volume of storm water being diverted off-site. Where an optimal storm water management system is installed on-site, the credit towards the storm water drainage system is proportional to the storm water falling on the roof, collected by gutters and sent to soakwells ($R_{soakwell}$), and to the storm water runoff on outdoor paved areas directed to soakwells ($S_{paved\_to\_soakwell}$). If a rainwater tank is present on-site, the volume of water retained in the tank (R_{tank_in}) and the tank overflow runoff to soakwells ($TO_{soakwell}$) constitute an additional credit towards the storm water drainage network (Table 2).

The concept of water debits towards the three man-made infrastructures refers to the volumes of water (i) consumed over time from the water supply network (i.e., mains water), (ii) discharged to sewerage (i.e., greywater and blackwater), and (iii) discharged to the drainage system (i.e., off-site runoff terms).

Although unexplored in the literature, the relationship between the hybrid water system and the aquifer can be quantified. The water debit towards the aquifer refers to the volumes of water extracted from the aquifer (G_{bore}, Table 2). A water debit towards the aquifer is also developed each time rainwater is used for indoor and outdoor uses (R_{tank_in}) as this disrupts the natural cycle of rainwater that would otherwise recharge the shallow aquifer. The water credit towards the aquifer aims at quantifying the on-site aquifer recharge due to an optimally designed storm water management system and is defined by the optimal redirection of tank overflow (TO) and storm water ($S_{paved\_to\_perm}$, $S_{paved\_to\_soakwell}$) towards aquifer recharge.

The value of credits and debits relative to each water infrastructure is calculated by summing the volumetric water flows of each water source over the chosen time horizon (Equation (4)):

$$\text{Credit or debit towards each water infrastructure} = \sum_{t=1}^{T} \sum_{i=1}^{WS} \text{Water Source}(i)(t) \quad (4)$$

where t is the time step used in the water balance (i.e., daily), WS is the total number of water sources used to calculate each credit–debit (Table 2) and T is the time horizon over which the credit–debit is calculated (e.g. hourly, daily, annual).

RESULTS AND DISCUSSION

The water demand at the study site over the year 2015 is shown in Figure 2 (daily aggregation of 10-minute volume data). The indoor water use is consistent throughout the

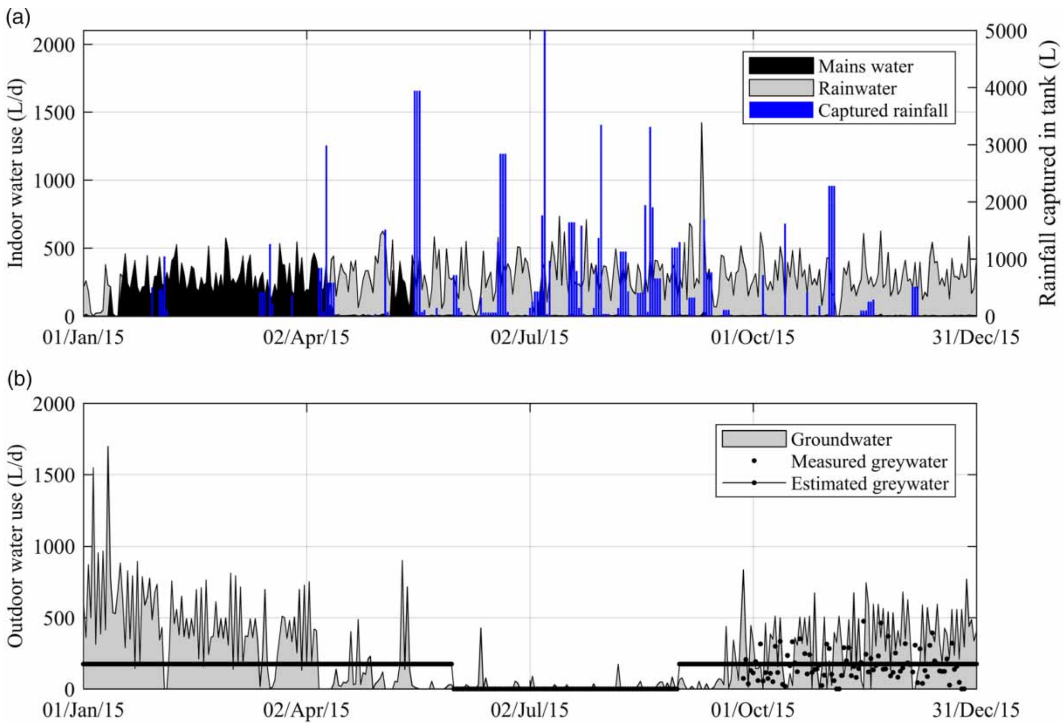


Figure 2 | Daily trend of (a) indoor and (b) outdoor water consumption over the year 2015.

whole year with an average and standard deviation (std) equal to 291 ± 155 l/d (Figure 2(a)). The average indoor water demand of 97 l/p/d at the study site is well below the Perth average of 160 l/p/d (Water Corporation 2010) due to water efficient fittings and water saving practices as discussed in Byrne (2016). Mains water is used almost exclusively during the summer months from January to March (average and std of 276 ± 125 l/d), when the rainwater tank is empty and rainfall is nearly absent (Figure 2(a)). As soon as increasing rainfall commences in April, mains water is almost entirely replaced by rainwater and the average use of mains water drops to 14 l/d.

The total outdoor water consumption is shown in Figure 2(b). The available measurements of greywater recorded from October to December 2015 (Figure 2(b)) were used to estimate the average value of 175 l/d, which is considered representative of the amount of greywater used for irrigation. A Perth residential water-use study (Water Corporation 2010) estimated the amount of daily produced wastewater to be equal to 85% of the indoor water demand, 75% of which was greywater (Table S1). Based on the average daily indoor use of 291 l/d, the greywater generated at the study site is estimated at 185 l/d, which compares well with the measured value of 175 l/d. For the sake of our modelling exercise, a greywater volume equal to 175 l/d is considered representative. The advent of ultrasonic unobstructed flow meters is expected to improve the measurability of greywater flows, thus allowing on-line monitoring of greywater sources. As shown by Figure 2(b), the majority of water used for irrigation is groundwater with an average value of 344 ± 277 l/d during the irrigation months. Note that in compliance with State Government law, irrigation is prohibited during the winter months (June–August).

Results for the 2015 water balance are summarized in Figure 1. As already observed in Figure 2, the MWN model (Byrne 2016) by which the study site has been built and operated allows a minimal use of mains water (29 kl over the entire year 2015, Figure 1), and null off-site runoff as all rain and storm waters are directed to the aquifer (Figure 1).

Water credits and debits are calculated for the current system (i.e., hybrid water system) and for the scenario where no hybrid water systems were installed (Table 3). Water debits are accrued towards the water supply network during summer months alone when the rainwater tank is empty and reliance on the water supply network for indoor use of potable water is necessary. For the rest of the year the site is almost fully independent from the mains water supply as a combination of alternative water sources is sufficient to meet both indoor and outdoor water demand. Daily values of water credits and debits towards the water supply network are shown in the Supplementary Material (Figure S2, available with the online version of this paper). In agreement with the literature (Daigger & Crawford 2007), a considerable saving of mains water and reduced discharge to sewerage (211 kl/y and 48 kl/y, respectively, Table 3) occur by using a diverse suite of water sources through a fit-for-purpose water quality hierarchy of uses. If a hybrid water system was not used, the reliance on the water supply network and sewerage network would increase by eight times and twice, respectively (Table 3). The reuse of greywater is seen as particularly beneficial as it generates credits towards both the water supply and sewerage network by reducing the use of mains water and the discharge to sewerage, without compromising the recharge to the aquifer. In their multi-objective optimization planning study, Newman *et al.* (2014) also recognized the importance of recycling wastewater on-site, thus suggesting local treatment of greywater and its use for indoor end-uses as a pathway worth investigating.

Table 3 | Water credits and debits calculated for 2015 in the case study

	Credit (kl)				**Debit (kl)**			
	Water supply network	**Sewerage network**	**Storm water drainage**	**Aquifer**	**Water supply network**	**Sewerage network**	**Storm water drainage**	**Aquifer**
Hybrid water system	211	48	98	120	29	43	0	157
Scenario with no hybrid water system	0	0	98	194	240	91	0	0

The quantification of credits developed by the resident towards the centralized water network leads to the introduction of a reward system to those residents who actively save energy-intensive mains water and wastewater. Although a water credit system is not new in industrial applications (Grieg-Gran *et al.* 2006) with the discussion commencing some years ago (Simus 2010), its application at residential scale has not been put into practice yet. We envisage that the integration of smart meters and a comprehensive accounting of all water flows can assist with the definition of a new financial framework where the water customer is encouraged to install and engage with localized and sustainable alternative water sources. Further economic analysis will be necessary if a new tariff is to be developed, and where the proposed reward system might account for both the consumption charges and infrastructure (annual service) charges.

The sustainability of hybrid water systems stems from a quantification of their impacts on the surrounding ecosystem, yet this aspect has largely been unexplored in the literature (Sapkota *et al.* 2014). At the study site, the storm water management system has been designed optimally to maximize aquifer recharge through soakwells and the absence of impervious surfaces, thus avoiding storm water off-site runoff (Byrne 2016). In 2015, 120 kl of water was estimated to recharge the aquifer (Figure 1 and Table 3), which offsets the debit developed towards the aquifer (157 kl/y, Table 3) by about 76%. Although the infiltration to the aquifer is optimized at the site, the presence of hybrid water systems generally reduces the total amount of water available for aquifer recharge. If the bore and rainwater tank were not installed, about 194 kl/y of water would have contributed to aquifer recharge during 2015 (Table 3, hypothetical scenario). The impact of a reduced recharge to aquifer following the adoption of hybrid water systems has to be considered to ensure the health of the aquifer as an ecosystem service. For example, the sustainable yield from the shallow aquifer in an ecosystem such as that existing in Perth will vary in space and time due to factors that might have policy implications, including soil type, depth to water table, extent of original vegetation clearing impact on evapotranspiration and extent of subsequent coverage by urban impermeable surfaces. The definition of credits, and potential reward to the residents, needs to consider the environmental role the aquifer plays in the water cycle and that recharge is maintained at a level consistent with sustainability principles.

CONCLUSIONS

The developed model provides a holistic accounting of the impacts of hybrid water systems on the centralized water and wastewater infrastructures at household-scale. The analyzed case study is an ideal testbed for the developed methodology as it integrates all the available alternative water systems with the centralized water supply grid. The introduction of water credits and debits via the water balance approach allows the quantification, and therefore valuation, of all water resources and all water uses, thus assisting with urban water management. Most importantly, introducing credits for on-site aquifer recharge and debits towards aquifer usage is equivalent to recognizing the importance of the shallow aquifer as an ecosystem service provider to the Perth urban water cycle. The introduction of a reward credit system to those residents who actively save energy-intensive mains water and wastewater whilst optimally managing the aquifer recharge enables a more sustainable use of water resources as well as assisting the water regulator in the definition of groundwater allocations and achievement of water savings targets. Current research conducted by the authors is focusing on integrating uncertainty analysis in the water balance as well as applying the methodology to a cohort of 36 households in the City of Fremantle, Western Australia.

ACKNOWLEDGEMENTS

Australian Government Department of Industry, Innovation and Science under the Smart Cities and Suburbs program funded this study under the RENeW Nexus project in the City of Fremantle, Western Australia.

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First received 15 February 2019; accepted in revised form 14 June 2019. Available online 27 June 2019