

Smart metering technology and community participation: investigating household water usage and perceived value of hybrid water systems

R. Fornarelli^{a,*}, M. Anda^b, S. Dallas^c and G. M. Morrison^c

^a Water Corporation, Perth, WA 6007, Australia

^b College of Science, Health, Engineering and Education, Murdoch University, 90 South Street, Murdoch 6150, Western Australia

^c Curtin University Sustainability Policy Institute, School of Design and the Built Environment, Curtin University, Kent Street, Bentley, WA 6102, Australia

*Corresponding author. E-mail: roberta.fornarelli@watercorporation.com.au

 SD, 0000-0003-4379-1482

ABSTRACT

Hybrid water systems (HWSs) are emerging as an alternative decentralised and cost-effective approach for urban water management. Although continuous monitoring is recognised as an essential step to inform the planning and design of water services, a knowledge gap has been identified in the integration of water use monitoring, HWSs and community participation. This research compares water practices of households with and without HWSs, integrating both quantitative and qualitative data. Water use data were collected at selected households via smart meters at 30 minute intervals. R computing software was used for data analytics and dashboard visualisation. Qualitative data on water practices was collected through one-to-one interviews, on-line surveys and community workshops. On a *per capita* basis, sites with HWSs have a 20% lower total water demand and 41% lower mains water demand than sites without HWSs. Depending on the level of sophistication of the installed HWS, the reduction of mains water use across the participants ranged from 20% to as high as 80%. Almost all sites with HWSs were able to meet the state government targets (40–60 kL/person/y) on annual per capita mains water usage. The seasonality of rainwater supply versus the weather-independent supply of greywater was observed in the data. The qualitative data collected during community engagement highlighted the importance of establishing a personal connection between the individual and the water resource and of involving the resident in the different stages of harvesting, using and disposing of water. This is expected to contribute to a higher perceived value of the water resources by improving awareness, making knowledge more accessible, improving the transparency between the community needs and the water utility decisions. To this end, the role of digital technologies in the water sector plays a role in assisting with the paradigm shift from centralised water networks to an integrated and community-empowered, centralised-hybrid water system.

Key words: community, digitisation, grey water, groundwater, hybrid water systems, rainwater

HIGHLIGHTS

- Analysis of water use, hybrid water systems (HWSs) and community participation.
- Per-capita HWSs sites total/mains water use is 20%–40% less than sites without HWSs.
- 20%–80% mains water demand reduction in households with HWSs.
- Digital technology to improve perceived value of water resources in the community.
- Need of a water tariff to respond to, and incentive for, water saving behaviours.

1. INTRODUCTION

1.1. Hybrid water systems in centralized urban water management

Challenged by the high variability in fresh water distribution, energy resources, and population growth, conventional urban water management (UWM) systems where drinking water is sourced from a centralised source, while wastewater is led away for disposal, are being increasingly scrutinized for their sustainability outcomes (Schmack *et al.* 2019). In Australia, a continuing expansion of centralized UWM systems has been considered inefficient, uneconomical and unsustainable (Quezada *et al.* 2016), thus calling for innovative regional and local assessments to identify optimal policy directions and technologies. A new interest in decentralized and diversified water solutions has emerged and they are considered cost effective, beneficial

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and possibly more sustainable and socially acceptable than traditional centralized systems (Ferguson *et al.* 2013; Rogers *et al.* 2015).

Hybrid water systems (HWSs) represent a decentralised and localised approach for sustainable water services, currently emerging as a complement to the centralised UWM (Tjandraatmadja *et al.* 2005; Sharma *et al.* 2013a). Incorporating one or several alternative water sources, HWSs have been defined by Sharma *et al.* (2013a) as ‘...systems provided for water, wastewater and stormwater services at the property, cluster and development scale that utilise alternative water resources including rainwater, wastewater and stormwater; based on a ‘fit for purpose’ concept. These systems can be managed as standalone systems, or integrated with centralised systems’. The benefits of HWSs include flexibility in implementation, a fit-for-purpose usage regime, reduced conveyance and considerable savings of energy-intensive mains water demand (Schmack *et al.* 2019, and references therein). These benefits in turn lead to the deferral of large new infrastructures and the maintenance of existing ones (Bieker *et al.* 2010; Sharma *et al.* 2010). However, HWSs face some challenges such as identification of spatial integration, economy of scale, energy intensity, social, economic and environmental viability (Schmack *et al.* 2019). On the technology side, the interactions between centralised and decentralised water supply services and the impact on the operational performance of the downstream infrastructure must be carefully considered for a large-scale HWS implementation to be successful (Schmack *et al.* 2019, and references therein).

1.2. Hybrid water systems in Australia

In Australia, the paradigm shift from a fully centralized to an integrated centralized-hybrid urban water system has been embodied in the concept of Water Sensitive Urban Design (WSUD) (Gardner *et al.* 2008). Similar to the concept of energy micro-grids, water micro-nets have been adopted as small-scale water systems interconnected to the existing centralized water and wastewater infrastructure (Falco & Webb 2015; Quezada *et al.* 2016). The implementation of energy and water micro-grids such as the White Gum Valley project and the Knutsford project in Western Australia (Byrne *et al.* 2019), the Aquarevo project in Melbourne (CRC for Water Sensitive Cities 2017) and the Capo di Monte project in Queensland (Sharma *et al.* 2013b), are examples of an optimal coexistence of the traditional centralized networks with innovative decentralized energy and water resources.

Although the transition towards a decentralised approach has started in Australia on a technological and, at a slower pace, on a governance level, the socio-technical implications of this transition have been left unexplored (Quezada *et al.* 2016). To address this gap, Quezada *et al.* (2016) analysed this transition in a social study revealing emerging tensions between water utilities, property developers and end-users. Beal & Flynn (2015) highlighted that this new shift in UWM must offer services that the resident wants or needs, thus a genuine consultation stage must be undertaken. To ensure needs are met and roles and responsibilities are clearly articulated, the transition from a traditional operation of water systems that is essentially invisible (towards the customer) and controlled by experts, towards locally integrated HWSs, requires three fundamental aspects. Firstly, from the water utility perspective, a robust understanding of water use practices adopted by those residents that already have HWSs installed at their household. Secondly, from the community perspective, a better understanding of the small-as well as large-scale urban water and wastewater system through increased stakeholder communication and engagement (Schmack *et al.* 2019). Thirdly, from the resident perspective, cost savings through a water tariff that rewards water efficient practices are of fundamental importance for the acceptance of HWSs on a large scale. The three aspects will be further discussed in the paper in the light of the findings of our study.

1.3. The digitisation of the water sector

The role of smart metering and data science is becoming increasingly recognised as an approach to assist with the planning and operation of urban water systems (Gurung *et al.* 2015; Nguyen *et al.* 2018; Cominola *et al.* 2019). Many studies integrate smart metering and mathematical modelling to monitor and understand residential water use as well as to plan and operate the urban water network (Gurung *et al.* 2015). The advent of ultrasonic Internet of Things (IoT)-connected smart meters has enabled the simplification and reduction in the costs associated with real-time residential-scale water flow monitoring for a range of water qualities (Stewart *et al.* 2018). Ultrasonic meters are capable of measuring alternative water supplies such as greywater, rainwater and groundwater without clogging, thus representing a step change in the ability to reliably and affordably quantify these volumes. Smart meters operating on IoT networks are currently being trialled by a number of Australian water utilities (AWA 2018) in order to further define upfront and on-going costs, battery life, and signal/reception issues.

From the community perspective, the social aspect of water saving and water use practices is recognized as enabling user awareness and leads to significant water savings (Anda *et al.* 2013; Fielding *et al.* 2013). By collecting and analysing high resolution water flow data, socio-demographic and lifestyle factors, environmental and water conservation attitudes can be drawn on to enable the potential transition towards a more sustainable UWM system (Grafton *et al.* 2011; Willis *et al.* 2013).

1.4. The knowledge gap and objective of this paper

We have identified a knowledge gap related to the integration of HWSs, community participation and water use monitoring as most studies are focused on scheme water only, with limited research on the continuous monitoring of household-scale HWSs (Gurung *et al.* 2015, 2016; Quezada *et al.* 2016). Although the collection of data on the use of HWSs is seen as an essential step to inform the planning and design of sustainable HWSs and the development of innovative services, Sharma *et al.* (2013b) is, to the best of the authors' knowledge, the only study that has monitored HWSs in Australia. No study has been found that integrates the smart metering of HWSs at the household scale with community perception of HWSs.

To address this gap, the Resilient Energy and Water Nexus (RENeW Nexus) project, an Australian-funded project under the National Smart Cities and Suburbs Program, was set to explore how smart cities can integrate data analytics, technological advances and community participation to improve the management of a distributed water infrastructure at the residential scale. The objective of this paper is to characterise and compare water use and supply across a cohort of selected households that have volunteered to be part of the RENEW Nexus project. This paper compares a group of houses with a traditional water system (i.e., connected to the centralised water supply and sewerage network) to a group of houses with HWSs (i.e., a combination of rainwater harvesting, greywater recycling and groundwater bores). The analysis of water use data is supported by qualitative data on the residents' water practices, collected through community participation initiatives such as site assessments, community focus groups and workshops. This is the first study in Western Australia, and one of the limited ones globally, that analyses and compares high frequency water demand data of neighbouring households with and without HWSs.

2. MATERIALS AND METHODS

2.1. Study sites

This study takes place in the metropolitan area of Western Australia. The potable water in the region is primarily supplied by the desalination of seawater (50%), some by groundwater extraction from a deep confined aquifer (40%) and a smaller fraction from surface catchment dams (10%), the former increasing over time and being an energy and capital-intensive source. It should be noted that the groundwater system in the studied area is comprised by three layers of aquifers, with the deepest confined layer being used to supply 40% of the potable water demand in the region. Of particular importance to our study is the shallow aquifer which stretches across the coastal plain and constitutes a shared water resource that has been exploited by the local residents for many decades. Whilst abstraction from the deep aquifer is licensed by the regulators for potable water supply only, the shallow aquifer is easily accessible by private groundwater bores, thus making the supply of water from the shallow aquifer a free, unlicensed and unmetered resource used by the residents for the irrigation of private lawns and gardens. Note that the focus of this paper is on the shallow aquifer only, as a water resource shared by the community.

As part of the RENEW Nexus project, the water use of a cohort of Western Australian residents was monitored for one year, from September 2018 to September 2019. The recruitment of households with HWSs was based on voluntary participation within the local government area of the City of Fremantle, which is located within the metropolitan area of Perth, the capital city of Western Australia (Figure 1(a)). The HWSs referred to in this study are either one of, or a combination of, plumbed rainwater tanks, greywater diversion systems, and privately-owned groundwater bores (Figure 1(b)). All RENEW Nexus houses are connected to the mains water supply network, which delivers high-quality potable water and is managed by the Western Australian water utility. Similarly, all houses are connected to the sewer network, which disposes into a separate wastewater system (Figure 1(b)). Only two sites with a private bore agreed to be part of the RENEW Nexus study, thus limited information is available for HWSs that include a groundwater bore (Table 1).

A cohort of 22 households was selected: 11 houses with HWSs and 11 houses without HWSs (hereafter referred to as Hybrid and MainsOnly sites, respectively). Although the sample size is limited, this study is important to inform the research community and water utilities as it is an unprecedented attempt to closely monitor water use of HWSs at the residential level and compare the results with an equivalent subset of houses without HWSs. The selected 22 houses are considered comparable as they are within the same local government area, are independent dwellings with similar occupancy (39 people in the

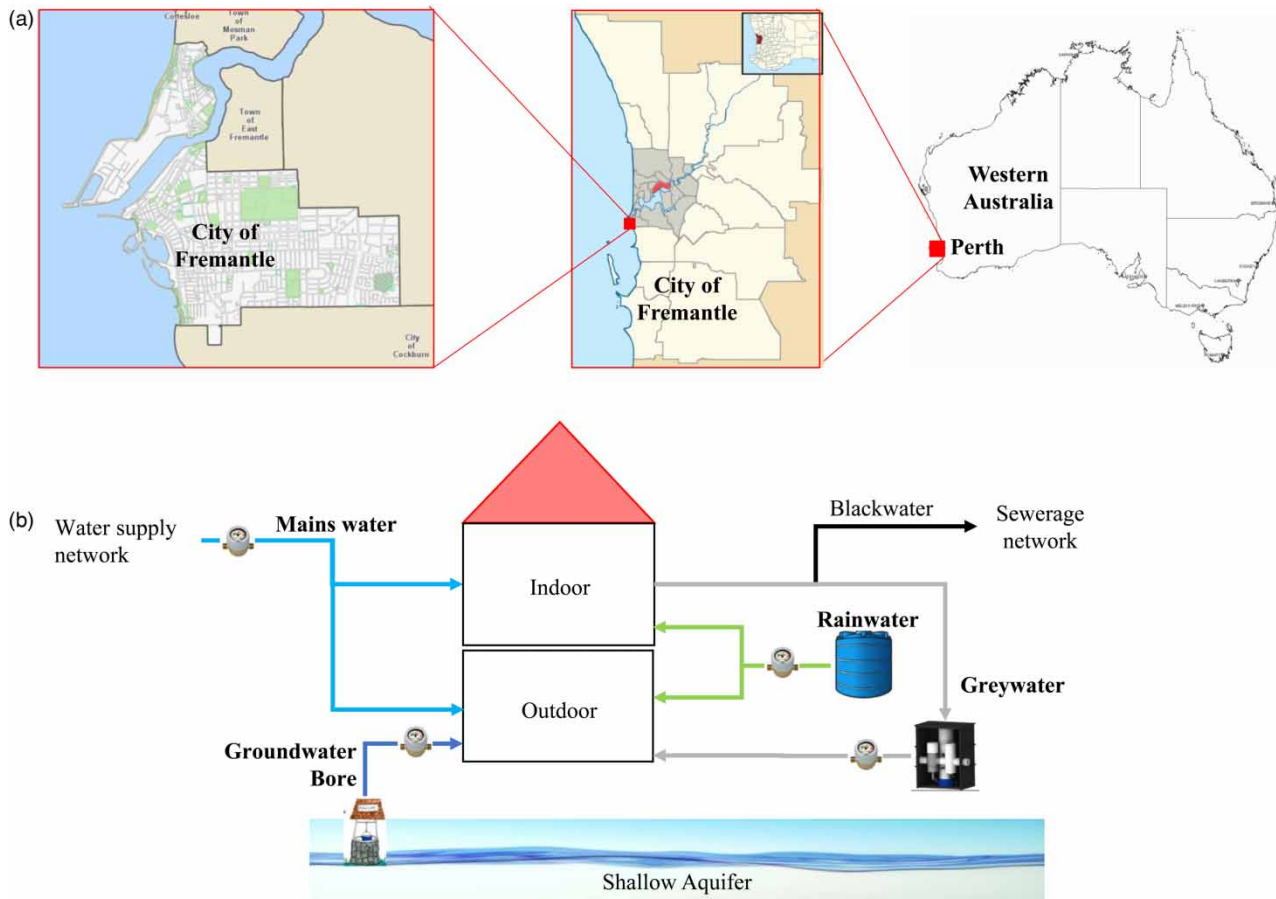



Figure 1 | (a) Study area and (b) schematic of a house with a full suite of HWSs installed. Smart meters are installed at the locations with symbol .

Mains Only sites and 36 people in the Hybrid sites, Table 1) and are characterised by similar lot sizes and outdoor areas. Site assessments of all the 22 sites and one-to-one interviews with the residents were undertaken to collect information about lot areas, outdoor landscape and vegetation, water use practices, occupancy and technical details of the installed HWSs.

2.2. Smart meters and data analytics

IoT-connected water flow meters were installed at the houses in August 2018. Meters were installed at each house from the supply point of each HWS as well as on the mains water line (Figure 1(b)). One water meter was installed at each MainsOnly site. Smart meters were installed at each HWS, plus one meter on the mains line. For example, for a house with a greywater diversion system and a rainwater tank, three smart meters were installed: one on the mains line, one on the outlet of the greywater diversion system and one on the outlet of the rainwater tank. The NU meter, a 20 mm ultrasonic revenue-grade smart meter from an Australian-based company (Water Group 2018) was selected amongst six off-the-shelf solutions available. This meter operates on the Telstra narrow band Internet of Things (NB-IoT) network and communicates to Cumulocity, a Telstra-owned cloud-based data management platform (Telstra 2018).

A total of 41 meters were installed at the selected houses (Table 1). Each meter recorded water volume readings every 30 minutes and communicated with the Cumulocity platform *via* the NB-IoT network once a day. Data were collected at each of the 22 houses, from 3 September 2018 until 31 August 2019, stored in the cloud-based system Cumulocity, and imported into R computing software to proceed with data analytics and visualisation.

To compare water use between MainsOnly and Hybrid sites, the following variables are calculated:

- Total Water Demand (TWD) which, for the Hybrid sites, is the sum of the readings of the meters installed on the mains line, rainwater tank outlet, greywater diversion system and groundwater bore, and for the MainsOnly sites is equivalent to the readings of the meter installed on the mains line;

Table 1 | Characterisation of the RENEW Nexus cohort of residential houses in the City of Fremantle, Western Australia

Site ID ^a	Water System	No. of installed water meters	Occupancy (no. of people living at the site) ^b
M.01	Mains	1	2
M.02	Mains	1	2
M.03	Mains	1	2
M.04	Mains	1	2
M.05	Mains	1	4
M.06	Mains	1	3
M.07	Mains	1	4
M.08	Mains	1	6
M.09	Mains	1	4
M.10	Mains	1	4
M.11	Mains	1	6
H.01	Mains + Rain + Grey + Bore	4	4
H.02	Mains + Rain	2	2
H.03	Mains + Rain + Grey	3	3
H.04	Mains + Rain	2	4
H.05	Mains + Rain + Grey	3	4
H.06	Mains + Rain + Grey + Bore	4	4
H.07	Mains + Rain + Grey	3	3
H.08	Mains + Rain	2	2
H.09	Mains + Grey	2	3
H.10	Mains + Rain + Grey	3	5
H.11	Mains + Rain	2	2

^aSites are de-identified. *M.* indicates MainsOnly sites; *H.* indicates Hybrid sites.

^bChanges in occupancy throughout the year occurred at some sites and are included in the calculations.

- Mains Water Demand (MWD) which is the equivalent to the readings of the meter installed on the mains line at every house. Note that TWD and MWD are the same quantities for MainsOnly sites.

HWSs have been recognised to abate the reliance on the mains water network by reducing the demand for high-quality expensive mains water (Lucas *et al.* 2010). For this reason, the comparison of MWD between the two cohorts is given particular attention in this paper. To this end, mains water savings are calculated for each household as the difference between TWD and MWD relative to the TWD. For example, for a household with HWSs, a water savings of 30% refers to that household consuming 30% less mains water as a result of the presence of HWSs installed at the house.

The raw water use data measured at 30-minute intervals have been aggregated hourly, daily and monthly to investigate daily and seasonal trends. The annual TWD and MWD at every site have been divided by each site's occupancy (Table 1) for comparison with the regional targets defined by the Western Australian water utility as well as by the WSUD framework (Department of Water 2008; Gardner *et al.* 2008).

2.3. Community participation

For the duration of RENEW Nexus, we engaged with the participants through a real-time visualisation platform, one-to-one interviews, two on-line surveys and three community workshops.

A real-time visualisation platform was provided to each participant so that water demand data from each source was visualised in real-time and at different time aggregation. The platform was built in an Amazon Web Service (AWS) environment and jointly developed by the authors of this paper and energyOS, an Australian digital service company (energyOS 2019).

A community workshop was organised with the intent to deepen our understanding of the value given by the participants to the four water sources; that is, potable scheme water, rainwater, greywater and groundwater. The participants were divided into focus groups and the facilitator of each group prompted a semi-structured discussion by asking the following three questions:

- Q1. How do you value water as a resource? (e.g. high quality water is more valuable than rainwater and groundwater, water is valued by its scarcity or by its cost of production).
- Q2. What motivated you to install, or not to install, an HWS? (e.g. mains water saving, lower bills, sustainability principles, not aware of them, too expensive, long payback).
- Q3. After decades of unlicensed and unmetered extraction by private garden bores, the quantity and quality of water in the shallow aquifer is declining. How should we best protect our shallow aquifer as a shared resource? (e.g. fees for licensing private bores, charge for meter and usage, apply an allocation limit).

The discussion on each workshop table was recorded and transcribed for analysis. It is recognised that the participants of RENEW Nexus can be defined as community champions (Lindsay *et al.* 2019) as they are self-motivated early adopters of new technological advances. Although not a statistically representative sample due to the limited sample size, the learnings from the community participation exercises are a useful source to inform researchers, water utilities and land developers on the community perception of HWSs and fit-for-purpose water use from a cohort of well-informed water users.

3. RESULTS AND DISCUSSION

3.1. Analysis of total water demand in the RENEW Nexus cohort

Across the entire monitoring year (September 2018–August 2019), the average daily TWD of the MainsOnly sites is significantly higher than the TWD of the Hybrid sites (as confirmed by p-values of a two-sided Kolmogorov-Smirnov test and a Mann-Whitney-Wilcoxon test being lower than 0.05). Hybrid sites use less mains water than MainsOnly sites, with an average daily MWD of 418 ± 484 L comparing to 786 ± 815 L for MainsOnly sites (Table 2). Overall, on an annual basis, the TWD and MWD of Hybrid sites are 23.5% and 46.5% lower than the TWD at MainsOnly sites, respectively (Table 2). On a *per capita* basis, Hybrid sites have a 20% lower TWD and 41% lower MWD than MainsOnly sites (Table 2).

The full dataset of daily TWD is shown in Figure 2(a) and 2(b) for MainsOnly and Hybrid sites, respectively. The monthly average values of TWD are similar between MainsOnly and Hybrid sites; however, the MWD of Hybrid sites is significantly lower than MainsOnly MWD (Figure 2(c)). Figure 2(d) shows the monthly trend of the TWD and MWD as a sum across the Hybrid and MainsOnly sites. The seasonal pattern is dominated by the irrigation occurring during the summer months: water demand for both cohorts increases through spring (from September to November) and reaches its maximum during the summer months of December, January and February. In order to reduce water consumption, permanent water restrictions are imposed in the Perth region on garden irrigation using mains water during the winter months, from 1 June to 31 August. Due to the irrigation halt imposed over winter, the TWD in June, July and August can be assumed to represent the indoor water demand at the MainsOnly sites. A constant TWD and MWD is measured in both cohorts across the winter months (Figure 2(c) and 2(d)).

The annual TWD and MWD at each site have been divided by the site occupancy (Table 1) to calculate *per capita* water demand over the year 2018–2019. It should be noted that changes in occupancy that occurred at different sites throughout the year were discussed with each participant during interviews and online surveys. Such changes were taken into account in the calculation of the annual *per capita* water demand. The *per capita* annual water demand is compared to the Perth residential average; that is, 106 kL/person/year (Water Corporation 2010), and to the WSUD aspirational targets; that is, between 40 and 60 kL/person/year of mains water (Department of Water 2008; Byrne *et al.* 2019). The WSUD framework has quantified that a reduction in annual consumption from the average of 106 kL/person/year to a target ranging between 40 and 60 kL/

Table 2 | Summary of water data measured at MainsOnly sites and Hybrid sites

	Sum over 1 year (kL)	Mean – daily (L)	Std – daily (L)	Min – daily (L)	Max – daily (L)
MainsOnly_TWD	2,913	786	815	0	11,089
Hybrids_TWD	2,220	607	566	0	9,056
Hybrids_MWD	1,569	418	484	0	9,054
MainsOnly_TWD <i>per capita</i>	888	240	298	0	5,545
Hybrids_TWD <i>per capita</i>	709	194	166	0	2,264
Hybrids_MWD <i>per capita</i>	520	142	149	0	2,264

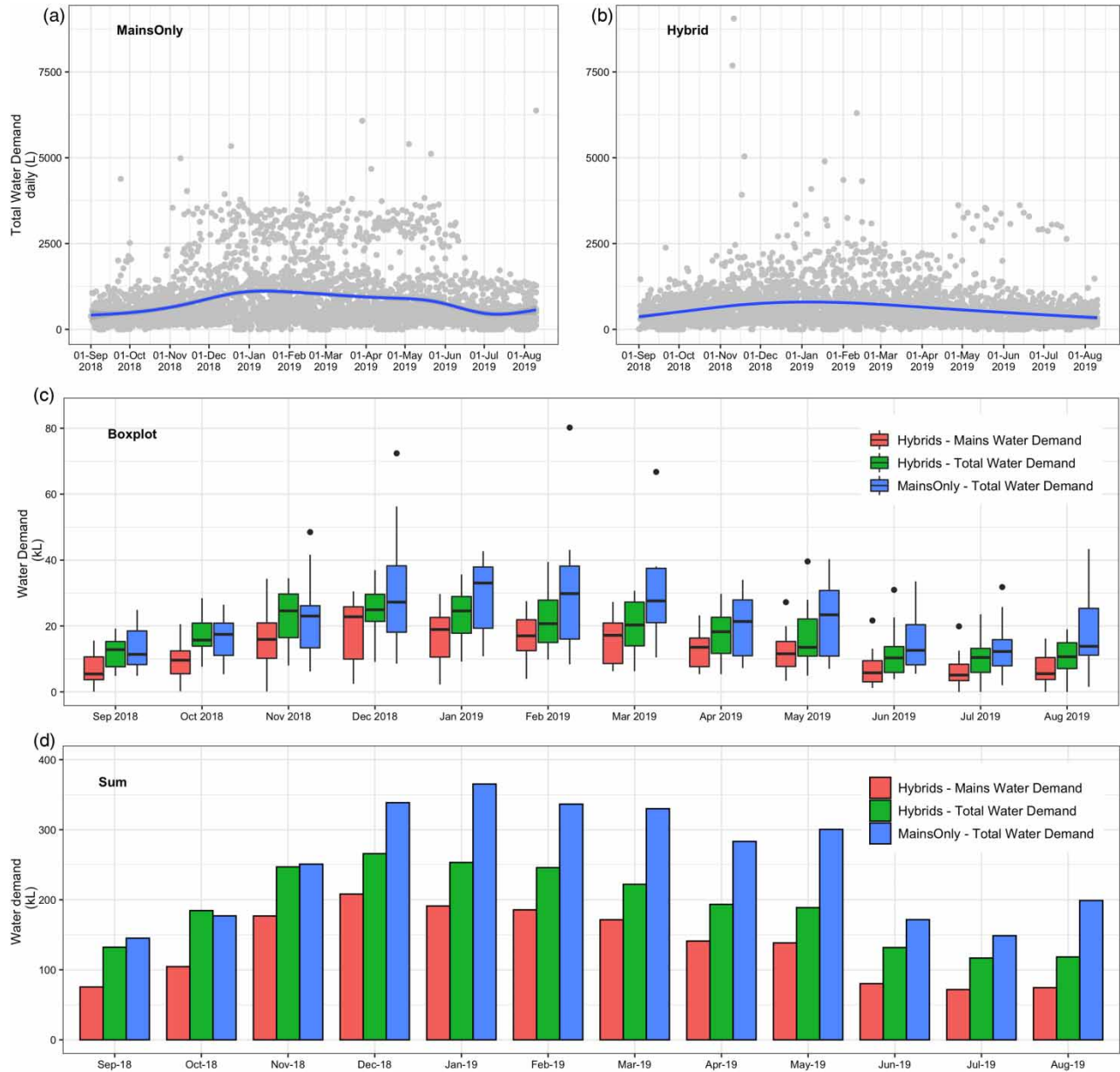


Figure 2 | Total water demand (TWD) and mains water demand (MWD) measured at MainsOnly and Hybrid sites.

person/year is possible through a series of structural, design and behavioural changes (Byrne *et al.* 2019). However, the impact of HWSs on the reduction of annual water demand has not been included in the WSUD principles as yet due to a lack of data on the use of HWSs. Although the RENEW Nexus study monitors the water demand of a limited cohort of residents, it can inform how the WSUD target could be further reduced by a combination of rainwater harvesting, greywater reuse and groundwater extraction. Figure 3 shows that MainsOnly sites have a very diverse *per capita* TWD with three sites largely exceeding the 106 kL/person/year target and one site lower than the WSUD target. The *per capita* TWD of Hybrid sites is below the Perth average with the majority of the sites sitting at, or within, the WSUD target (Figure 3).

Four sites (H.01, H.06, H.07 and H.08 in Figure 3) are characterized by a very low *per capita* MWD, which is below the lower WSUD target of 40 kL/person/year. During the year, the mains water savings measured at the Hybrid sites with a full suite of HWSs are 55 and 84% (sites H.01 and H.06 in Figure 3). These sites are characterized by a fully comprehensive HWS with rainwater tank, greywater diversion system and groundwater bore, thus suggesting this configuration might be the optimal one to minimise the dependency on energy-intensive mains water.

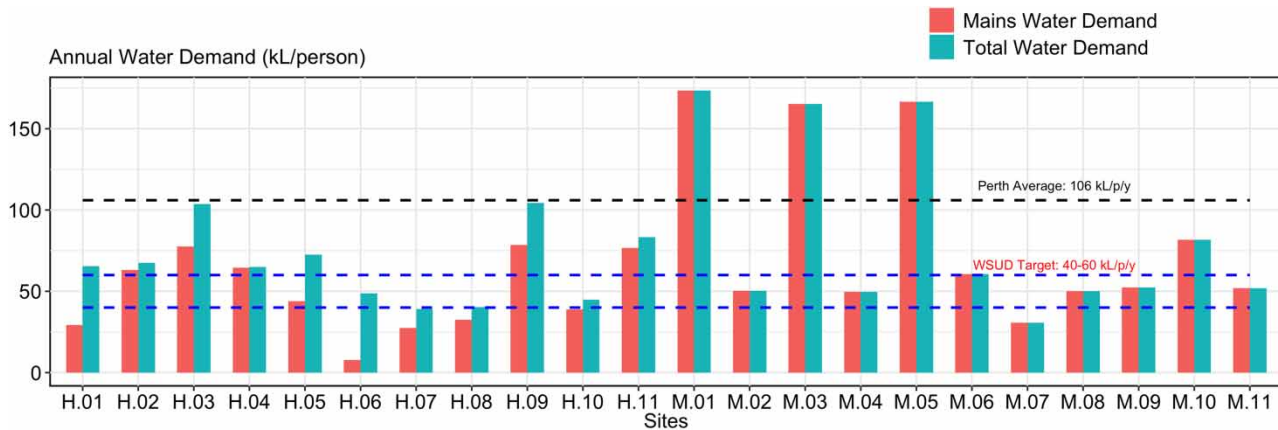


Figure 3 | Annual *per capita* total and mains water demand (TWD and MWD) for each site.

The Hybrid sites with a combination of rainwater harvesting and greywater reuse have achieved mains water savings ranging from 13% to 39% (Figure 3), which compares with the range given by Ghisi & Ferreira (2007). It should be noted that site H.05 achieves a 39% mains water saving by an optimal combination of rainwater and greywater reuse: when available over winter, rainwater is used for all indoor uses whilst greywater is partially diverted to the garden and partially reused in the house for toilet flushing and washing machine operation.

The Hybrid sites with rainwater harvesting as the only HWS achieve an annual saving of mains water of about 11% (H.02, H.08 and H.11 in Figure 3), with a maximum of 19% and a minimum of 6%. This result is consistent with values reported in the literature (Ghisi & Ferreira 2007; Gurung *et al.* 2015). The highly seasonal rainfall pattern in the studied region represents a challenge for residential rainwater harvesting due to the limited storage capacity of the household tanks. In order to maximise the yield from rainfall harvesting, community-shared storage tanks should be investigated as a potential cost-effective solution for future residential developments.

3.2. Analysis of water supply by source in the RENew Nexus cohort

The water supply by source at the Hybrid sites is represented in Figure 4. Due to some sites having different combinations of HWSs, sites are divided into Hybrid_RGB (Hybrid sites with a full suite of HWSs, i.e. rainwater harvesting, groundwater bore and greywater recycle), Hybrid_RG (sites with rainwater harvesting and greywater recycle) and Hybrid_R (sites with rainwater harvesting only).

Across all sites, rainwater is a significant source of supply from June to October/November depending on the size of the tanks and the end use. When available, rainwater supply contributes between 20 and 45% of the TWD; however, due to the limited availability of storage space, its contribution becomes negligible during summer and fall (Figure 4). In both the Hybrid_RGB sites, groundwater is used for outdoor irrigation only and thus meets a large portion of the TWD during spring and summer (Figure 4(a), 50% average percentage contribution to TWD). Interestingly, greywater represents a source of water supply that is reliably available throughout the year at all sites and contributes a consistent 10% to 20% through the whole year (Figure 4(a) and 4(b)). The reliability and time-independent supply of greywater make this source of water particularly attractive for planning purposes as further discussed in the following sections.

3.3. Community perception of water resources

To better understand the attitude of the consumers towards HWSs and water resources, community engagement initiatives with the RENew Nexus participants were organised as part of the project. The answers of the participants to the facilitator's questions discussed during the community workshop are summarised in Table 3.

The value the participants give to water is dependent on several factors, which are ranked below from the highest to lowest level of importance:

- Water is valued by its scarcity: the scarcer and more finite the resource is, the higher the value given. In this context rainwater is perceived as more valuable than the other sources.

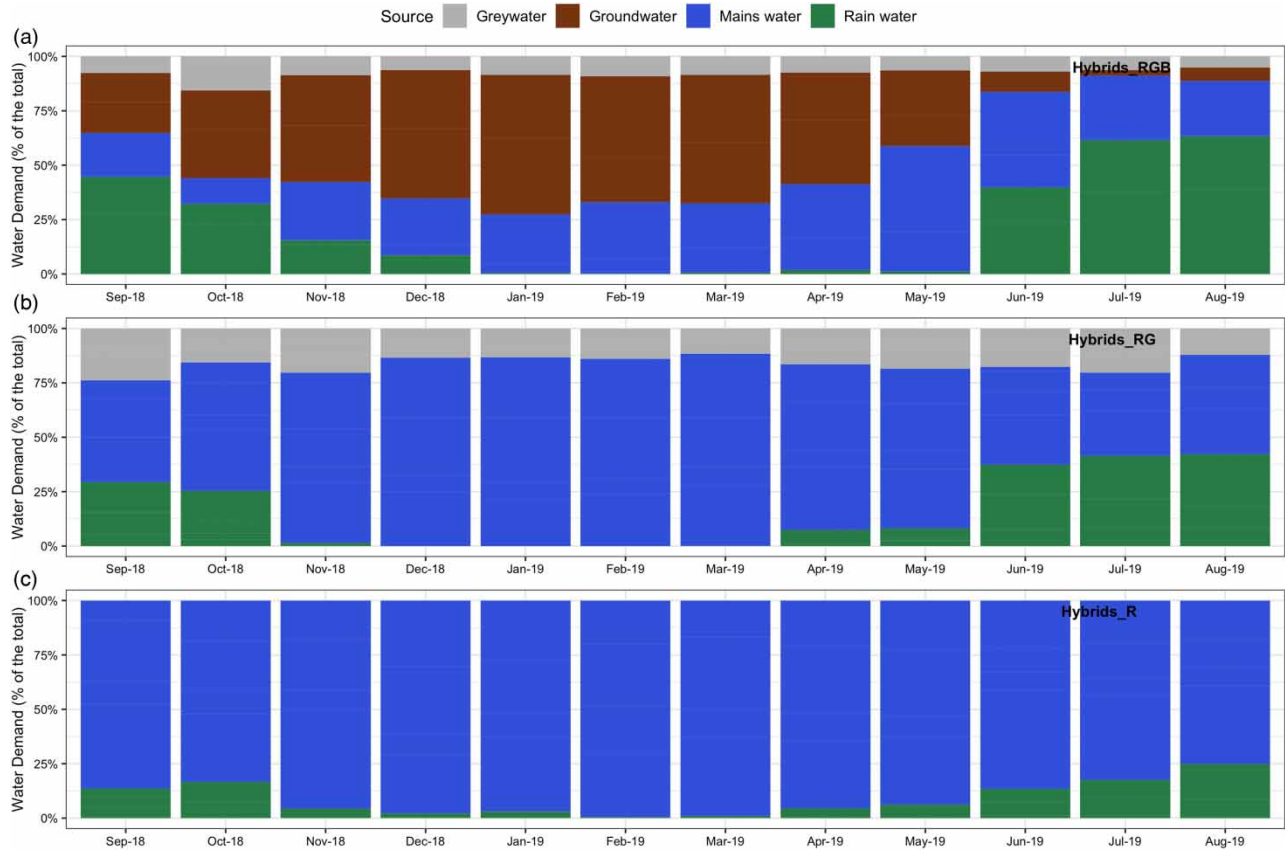


Figure 4 | Water demand by source (as percentage of the total) at Hybrid sites with different combinations of hybrid systems (RGB: rain, grey, bore; RG: rain, grey; R: rain).

Table 3 | Outcomes of the community engagement workshop with the RENEW Nexus participants

Questions	Answers ranked from high to low importance
Q1. How do you value water as a resource?	By its scarcity > rainwater has the highest value By its tangible and intangible cost of production: effort to produce/harvest/treat/convey > HWSs have the highest value By its generated energy savings: ability to displace energy intensive mains water > HWSs have the highest value By its end use: different sources have different values depending on their final use > mains and rainwater have highest value By its generated financial savings: need for a water tariff that would place more value on the actual water used > HWSs have the highest value
Q2. What motivated you to install, or not to install, an HWS	Sustainability and recycling attitude Value of the resource as a whole – Water is too precious not to collect it Freedom to irrigate private gardens all year around Too expensive infrastructure – Lack of rebates and subsidies Retrofitting is not practical Small garden size
Q3. How should we best protect our shallow aquifer as a shared ecosystem?	Licensing, monitoring and allocation limits to existing and new bores Management at local government scale to target local irrigation needs and aquifer health Education on the shallow aquifer as a shared resource and ecosystem service provider Smart water-wise irrigation systems

- Water is valued in relation to the effort made to produce it: the greater the effort, the more valuable the water. The participants define the effort not only as the tangible financial cost incurred to install a rainwater tank, but further as the intangible effort the consumer has gone through to generate a supply of water for the household. In this context, the value of the water resource is related to the time the consumer dedicates to install, understand the technical complexities, become familiar with and use the chosen technology. Rainwater and greywater are perceived as more valuable as each participant who has such technologies invested the time, intellect and financial cost to install the chosen system.
- Water is valued in relation to generated energy savings. In this context, alternative water systems (i.e. rainwater, greywater and groundwater) are perceived as highly valuable as their use displaces the use of mains water that, in the context of the study area, is energy intensive as it is sourced from desalination and deep aquifer extraction.
- Water is valued in relation to its end use: the higher the importance of a specific end use is for the user, the more valuable the water source.

The absence of any substantial financial incentives towards saving water, whether in the form of rebates on HWSs, savings from reduced wastewater discharged to sewer or as the monetary price paid per unit of water used, has discouraged some of the participants from installing HWSs. The perceived complexity of installation and a low irrigation demand are also reasons why some participants chose not to install HWSs. On the contrary, residents with HWSs have decided to do so based on sustainability principles and the scarcity of the water resource, i.e. ‘water is just too precious not to collect and recycle it’ (RENeW Nexus participant, personal communication, April 2019) (Table 3), despite the financial investment and the lack of support from the State government. This attitude is typical of early adopters (Lindsay *et al.* 2019), as they have decided to adopt new and innovative technologies, not necessarily driven by a financial return, rather by sustainability principles and a community-driven attitude. Although this represents a small percentage of the community, this initiative is recognised as important for demonstration and becomes the precursor for the adoption of new technologies at a larger scale.

The use of the shallow aquifer for personal water bores was discussed by participants in the workshop as an example of the tragedy of the commons (Hardin 1968), as it is a shared resource exploited by the residents without the necessary awareness and regulation to preserve the aquifer’s ecosystem value. The loose regulation on groundwater extraction from the shallow aquifer, which currently allows privately owned bores (estimated as approximately 190,000 in total across the Perth metropolitan area abstracting up to 82 GL per year, Department of Water 2020) to freely access this unmonitored water resource, was discussed as largely devaluing the importance of the shallow aquifer. The cohort of the interviewed participants agreed on the need for better regulation at the local government level, smart monitoring of new and existing bores, as well as an education program on the ecosystem services provided by the aquifer. The Western Australian government is currently evaluating a new framework to manage groundwater accessibility from the shallow aquifer (Government of Western Australia 2019).

3.4. The future of Hybrid Water Systems in cities

Depending on the level of sophistication of the installed HWS, the reduction of mains water use across the RENEW Nexus participants ranged from 20% to as high as 80%. Although a comprehensive cost benefit analysis and techno-economic assessment is required to fully quantify the financial benefit of a large-scale rollout of HWSs in this region and relevant cities generally, the mains water savings measured in this study support the argument that HWSs can lead to a significant financial return for the water utility in the context of the deferral of capital-intensive infrastructures (i.e. a third desalination plant in the Perth region, Water Corporation 2019). Modelling the impacts of an extensive rollout of HWSs is outside the scope of this paper; however, some key learnings of the RENEW Nexus study that contribute to integrate smart-metering and community engagement as well as to assist water utilities in their future planning are discussed below for each water source.

Rainwater was considered a high value water source due its scarcity in this region, end use adaptability and the inherent effort involved with its collection and use (i.e. financial cost of production and effort required for installation). This study shows how the personal connection between the consumer and rainwater harvesting contributes to a high perceived value of this water source, which translates into an efficient use. In order to leverage such a connection, it is recommended that an integration of household-scale and precinct-scale community-owned rainwater tanks might be an optimal solution to account for rainfall seasonal patterns (i.e. maximise the available storage) whilst maintaining the one-to-one engagement of the consumer in rainwater collection, and thereby its perceived high value.

Greywater is currently an under-utilized resource despite its production being constant over time and weather independent, the high value attributed by consumers, and its widespread use worldwide (Vuppaladadiyam *et al.* 2019). The all-year round

availability of greywater is highly valued by the interviewed participants as it allows them to meet their end uses, such as outdoor garden irrigation, without restrictions. Moreover, the reuse of greywater has been shown to provide double benefits by displacing mains water for irrigation and by reducing the amount of wastewater sent for further treatment (Fornarelli *et al.* 2019). The rebound effect was discussed in the community workshop as a potential undesired side effect of greywater reuse; that is, longer shower time or more frequent washing cycles can result as a consequence of the direct diversion of greywater towards garden irrigation. The advancement of smaller, cheaper and easier-to-install smart metering technologies, in conjunction with new digital water quality sensor solutions (Xu *et al.* 2019), data visualisation tools and education programs can support the emergence of a new home system of practice for water with avoidance of rebound effects while promoting awareness of consumption and resource management (Eon *et al.* 2018).

Groundwater extracted from the shallow aquifer is currently a free resource, unlicensed and unmetered by the water utility. The ecosystem services offered by the aquifer and the implications of over extraction on the quality of its water are poorly understood by the community. The ease of accessibility and the perceived unlimited supply makes the value of this water source low. Lack of regulation and the unwillingness of the consumers to share their use of groundwater contribute to over-exploitation and a perceived low economic, social and environmental value for this resource. It is recommended that a regulatory framework be developed to better manage private garden bores.

The discussion on the value of water and on HWSs prompted a conversation on the block water tariff for residential customers, and how to incentivise the greater community to reduce water usage. Although the RENEW Nexus cohort installed HWSs through their own will, without financial incentives to do so, it is expected that the adoption of these technologies at a larger scale needs to provide tangible economic benefits to the consumers in order to effectively reduce the reliance on the mains water network. Observations and recommendations were:

- Volumetric use of water should be charged at more than the current rates to incentivise consumers to reduce consumption and reward those who reduce water usage.
- The current tariff, which charges wastewater proportionally to the rateable value of the property (which is mostly based on the housing market), devalues wastewater despite the potential for greywater to be directly recycled and used for irrigation.
- Having recognised the value of HWSs in saving mains water (thus possibly deferring capital intensive infrastructures), a percentage discount on the fixed charges could incentivise consumers to adopt HWSs.
- By monitoring demand and supply of water at high frequencies, smart meters can support a new water pricing framework where the seasonality of supply and demand is taken into account (Stephan & Stephan 2017; Nguyen *et al.* 2018).
- A new mains water tariff and continuous education programs are perceived as necessary tools to improve the relationship with all water sources and maximise their value as perceived by the community.

The provision of a real-time visualisation platform to every participant of RENEW Nexus was perceived as extremely beneficial by the consumers and there was a general agreement of the need for real-time monitoring displays to be engaging, user-friendly and meet household needs. The participants actively used the dashboard to regulate the use of water for irrigation and to benchmark their actual water consumption against their own perceived consumption. Together with suggesting a demand-driven water tariff, the cohort of RENEW Nexus participants suggested leveraging the new smart meter technology and progress in data science to further develop real-time visualisation tools that inform the consumer how much and where water is used. These findings corroborate the need for adoption and expansion of digital technologies in the water sector (Quezada *et al.* 2016; Nguyen *et al.* 2018).

4. CONCLUSIONS

This paper describes water use practices for a group of metropolitan households and compares sites with mains water connection only to sites with HWSs. The smart-metered water demand exhibits a strong seasonal trend with higher usage during spring and summer for irrigation and a relatively low use during the winter months. Overall, the TWD of MainsOnly and Hybrid sites is similar; however, a reduction of mains water usage equivalent to 50–80% and 20–40% is obtained at sites with a full suite of HWSs and sites with rainwater and greywater systems, respectively. On a *per-capita* basis, HWSs reduce total and mains water consumption by 20 and 41%, respectively.

The integration of quantitative data and community participation data provides some insights into possible scenarios where HWSs are integrated with the centralized system. In particular, it is recommended to reduce the dependence on garden bores as the unregulated use of a shared resource that is poorly understood by the general public leads to the de-valuing of the water

source. The perception of rainwater as a precious resource is well accepted by the community as a consequence of the direct engagement of the residents with their own rainwater harvesting system. A balance between household and community-scale rainwater tanks is recommended to maximise rainwater storage whilst maintaining a personal engagement with the water resource. The value of greywater as a weather-independent resource that concomitantly minimizes the use of mains water and reduces wastewater generation remains underestimated by the water utility. By leveraging the advancement in cost-effective smart meters and water quality sensor solutions, systems that promote the reuse of greywater for indoor applications as well as for outdoor irrigation are recommended. The discussion on the value of water sources and HWSs highlighted the need for a water tariff that better responds to, and provides incentives for new, water saving behaviours, as well as valuing the importance of HWSs in, for example, deferred capital-intensive infrastructures.

In all the aspects analysed in this paper (e.g. community engagement, water efficiencies, water value and water tariff), the role of digital technologies in the water sector is vital to assist with the new shift from centralised water networks to a community-empowered, integrated, centralised-hybrid water system.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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