Real-world sustainability analysis of an innovative decentralized water system with rainwater harvesting and wastewater reclamation

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1. Introduction

Climate change is predicted to increase vulnerability of global water resources, and rising human water demands are an even bigger threat to global water security (Vörösmarty et al., 2000). Domestic water demand in the world is projected to increase from 235 km$^3$ in 2010 to 290 km$^3$ in 2025. Most of this increase is projected for low- and middle-income countries due to their higher population growth rates, relatively rapid urbanisation and increase of per capita water use from the existing low levels, due to income growth (Rosegrant and Cai, 2002). With more than 80 percent of wastewater currently being discharged into rivers or the sea without treatment, there exists an enormous wastewater infrastructure investment need (UN, 2020). However, conventional water supply and wastewater treatment systems are very energy intensive (Liu et al., 2016), and provide questionable templates for water infrastructure expansion in low- and middle-income countries (Mohapatra et al., 2014). Global electricity consumption in the water sector by process was already 330, 150, 280, and 70 Terawatt hours (TWh) in 2014, for water supply, distribution, wastewater treatment and transfer, respectively, with a rate of increase of 8% (WEO, 2019). Current templates and policies need to be rethought for more sustainable urban water systems in both developed (Hering et al., 2013) and developing countries. For example, the Central Ground Water Authority (CGWA) of India has issued an advisory to take necessary measures for adopting rainwater harvesting (Panda, 2015), and various Indian states have made rainwater harvesting mandatory by enacting laws and formulating rules and
regulations, including provisions in building bye-laws. Decentralized water and wastewater treatment systems are considered more sustainable than centralized systems (Chirisa et al., 2017; Massoud et al., 2009; Peter-Varbanets et al., 2009; Roefs et al., 2017). Decentralized systems can reduce the energy demand for water conveyance and reclaim water for local re-use (Gikas and Tchobanoglous, 2009). However, not much original data is available to support these contentions, as decentralized water treatment systems have only rarely been monitored in a real-world setting (Bhakar et al., 2015). In addition, economic aspects of new technologies such as affordability are critically important for water infrastructure expansion in low- and middle-income countries. Management optimization can be as effective as technological innovations in reducing pressure on water resources (Amores et al., 2013; Massoud et al., 2009). Ground-truthing is needed to firmly establish the legitimacy of emerging water treatment and reuse technologies (Binz et al., 2016).

To address these knowledge gaps, this study reports on the real-world performance of a decentralized water system which was recently built with sustainability as a core design criterion. The system was built in India for a higher education institution with student and staff accommodation and included rainwater harvesting, aeration-free wastewater treatment, and 100% wastewater reclamation to reduce pressure on blue water resources in a semi-arid region. The real-world data enabled a scenario analysis to critically compare the investigated

Fig. 1. A) Schematic diagram of the decentralized water system with its components, water meter, electricity meter and pump locations. B) Schematic illustration of the data acquisition methods.
system with more conventional and alternative design solutions, and to identify water systems management optimization strategies.

2. Methodology

2.1. Site choice

This study investigated a decentralized water and wastewater treatment system providing for a recently established campus located in a hot, semi-arid region of India with a summer, monsoon and winter season. Annual precipitation in the region is about 751 mm according to the institutional records, and 741 mm according to Indian Meteorological Department (IMD) data for the period of 1971–2000, and largely confined to the months of June–September. The campus development started with the purchase of land in a rural setting, and included at the time of the monitoring teaching, laboratory and office buildings, student dormitories and staff accommodation, catering and recreational facilities. Sustainability had been a guiding principle for this campus development, which provided in a microcosm the vision of leading Indian engineers of how a more sustainable urban future in India might look like. Activities on the new campus began in 2015, and the monitoring took place in the calendar year 2018.

2.2. Description of the decentralized water system and data collection

The institutional water system is illustrated in Fig. 1a. The drinking water treatment plant (DWTP) relied on river water and a rainwater harvesting system for its water resources. River water was provided for a volumetric charge by an external company, while the rainwater was harvested from building roofs on campus as a local source for potable water production. The drinking water treatment processes were primary disinfectant dosing into the inlet chamber, flash mixing, clariflocculation, multi grade sand filtration and final disinfection with chlorine. Poly Aluminium Chloride (PAC) was used as coagulant dosed into the raw water, and sodium hypochlorite (NaClO) was used as disinfectant. The Wastewater Treatment Plant (WWTP) treated and reclaimed wastewater produced on campus for re-use in ground maintenance and irrigation without the energy-intensive, pumped aeration of conventional wastewater treatment. The wastewater treatment processes were primary multi-level grid settling followed by an anaerobic baffled reactor and a planted gravel filtration constructed wetland with Canna plants, pressurized sand filtration, and disinfection by UV. Sodium hypochlorite was added to the reclaimed water to provide a disinfectant residual in the distribution system in case of accidental drinking from the irrigation pipes.

The DWTP outflow was conveyed via the drinking water pumping station (DWPS) to the drinking water service centre (DWSC). Some potable water was then diverted to the reclaimed water service centre (RWSC) to be used for toilet flushing. Contrary to the original design, no reclaimed water was being used for toilet flushing. The sewage volume collected from the housing, hostel and teaching areas was conveyed via sewers and the wastewater pumping station for treatment in the WWTP. The WWTP effluent was reclaimed and intermittently stored at the reclaimed water pumping station (RWPS) to be conveyed for ground maintenance to the housing, hostel and teaching areas, and to irrigate the scenic area and sports grounds. During the wet season, some reclaimed water was being transferred to an artificial lake on campus for storage. Flows were recorded by various water meters (Fig. 1a). Energy area consumption meters were installed for different zones of the water system (Fig. 1a). Chemical consumption data was available from monthly maintenance reports. Infrastructure and operational costs (incl. staff) were available from the institution’s development faculty. The data collection methods are illustrated in Fig. 1b, and further detail is provided as supporting information, which also contains the monthly data compilations (Tables S1-3).

2.3. Scenario analysis

The data informed scenarios to analyse the cost/benefits of individual water system components and alternative system designs. For each scenario, the annual volume of externally sourced blue water (river water), electricity consumption, chemical consumption, operational costs and infrastructure costs were compared. A baseline scenario was developed for a more conventional design, which sources all the water needed off-site from the river (100% blue water), treating it to potable standards. This scenario was used as a reference to evaluate the sustainability of more innovative treatment system components, which includes rainwater harvesting and wastewater reclaimed, as outlined...
in Fig. 1a. The second scenario considered the current system minus the wastewater reclamation infrastructure to investigate the sustainability of rainwater harvesting in isolation. The third design scenario considered the current system minus the rainwater harvesting infrastructure, and with reduced reclaimed wastewater infrastructures, keeping only those components needed to reclaim water for ground maintenance. The assessment of the economic sustainability of each system with more innovative features then relied on the payback period when the accumulated operational costs savings were expected to exceed the capital investment costs for these features (i.e. rainwater harvesting and/or wastewater reclamation related infrastructures). Payback periods for infrastructure capital costs were calculated as the number of years when the net present value of the operational cost savings achieved with these infrastructure investments would become positive. For this calculation, it was assumed that operational costs would increase with a constant rate of inflation (4.86% for India in 2018). The discount rate was taken as the corresponding Bank of India interest rate (6.5%), which could be earned on an alternative investment. Furthermore, scenarios were developed for the current system design, but without leakage, or with drought tolerant landscaping to reduce the irrigation water demand, in order to assess opportunities for better system maintenance and management. The assumptions for each scenario with diagrams of the various design alternatives and the related calculation formulas are provided as supporting information, incl. Figure S1.

3. Results and discussion

3.1. Use of different water resources

The institutional water use in the calendar year 2018 was 379,768 m$^3$ to provide for the need of 2468 students, staff and family members living, working and being educated on campus. 39% of the water resources needed were either collected (rainwater, 7%), or regenerated (reclaimed water, 32%) on campus (Fig. 2a). Treated rainwater could meet up to 42% of the institutional potable water use in the month of August at the height of the monsoon season but contributed little water during the months of October to Mai. While these significant water system achievements substantially reduced blue water abstraction (i.e. surface or ground water) in a semi-arid region, the absolute abstraction volume is also influenced by the water demand.

3.2. Water demands

The institutional water demand per person living on campus was 403 L per capita per day (LPCD). For comparison, a lower institutional water demand of 329 LPCD has been reported for another university campus in India by Bhakar et al. (2015). The average per person water demand for different usages (Fig. 2b) was derived from the meter recordings at the water service centres during the nine months with full housing occupancy. The potable water demand for the student housing area was 154.2 LPCD, of which 57.9 LPCD were used for toilet flushing (37.6%). In the academic housing area, the potable water demand was 222.7 LPCD, of which 66.2 LPCD were used for toilet flushing (29.7%). A similar average domestic water use of 218 LPCD for flats/apartments with a family of four has been reported based on a questionnaire survey of households in Jaipur, India by Sadr et al. (2016). Rosegrant and Cal (2002) quoted an average domestic water demand of 93 LPCD in developing countries and 140 LPCD in developed countries in 2010. The 223 LPCD domestic water demand in the academic housing area was 280% higher than the average 79 LPCD for India in 2010 quoted by Rosegrant and Cal (2002), and more in-line with the 247 LPCD quoted for the USA. The increasing per capita water use of more affluent consumers in middle income countries presents a significant water infrastructure development and water resources management challenge. In this study, the 280% increase in domestic academic demand, as compared to the Indian national median in 2010, is much higher than the 7% reduction in river water use achieved by rainwater harvesting. No reclaimed wastewater was used for domestic purposes. Domestic water consumption could be reduced through installation of more water efficient appliances, the timely repair of malfunctioning appliances, and water user education. A survey of student dormitories identified some malfunctioning appliances: seven leaking taps of which one was leaking heavily, and three constantly running toilets of which two were running heavily. Water demands in the teaching buildings and laboratories were 98.1 LPCD, of which 47.0 LPCD were used for toilet flushing (47.9%). Reclaimed water use was 365 m$^3$/d, equivalent to 148 LPCD during the months with full occupancy. The reclaimed water going to the housing and teaching areas for ground maintenance activities such as cleaning and irrigation was 284 m$^3$/d. Consequently, reclaimed water going to the sports ground and scenic areas for irrigation was 81 m$^3$/d. Engagement with the ground maintenance team revealed that reclaimed water demand for cleaning activities was around 52 m$^3$/d, whereas potable water demand for indoor ground cleaning was around 32 m$^3$/d. In summary, the institutional water demand was high in comparison with other reported values for India and beyond (Table S4 in supporting information), mainly due to the high irrigation and ground maintenance water demand. Most of the reclaimed water was being used for irrigation of greenery around the student and staff housing areas. A change towards lower water demand landscaping could free up significant reclaimed water volumes, which could be used to meet the institutional toilet flushing demand, as originally intended in the water system design (Fig. 1). Incomplete resource recovery due to water leakage from the system may also explain why insufficient reclaimed water was available to meet all non-potable demands. Limited availability was the main reason why no reclaimed water was being used for toilet flushing, as originally intended, but potential concerns about reclaimed water quality may have been a contributing factor.

3.3. Leakage and other water losses from the system

Metered water flows at different observation points in the water network are compared in Fig. 3. Decreasing flow in the downstream direction indicates water use for purposes, where the water was not returned to the sewer, and/or leakage from the system. The biggest flow reduction of 47% was between the drinking water service centre (DWSC1+2 + 3) and the collected wastewater volume (S1+2). Some of the water used by households and students for cleaning, car washing, cooking and drinking, may have been lost to the soil and by evaporation, but such losses tend to be small. The potable water demand for indoor ground cleaning can for example explain 11% (i.e. 32 m$^3$/d of the 294 m$^3$/d) of the flow reduction observed between DWSC1+2 + 3 and S1+S2. Leakage from the pressurized pipes or the sewers were likely additional causes of the significant flow discrepancy. One significant leak from an above-ground pressurized pipe was identified during a
decentralized system consumed 25,207 kWh/month of energy, which is 4% of national electricity usage in 2002 (Parkinson and Tayler, 2003). The contribution of institutional renewable electricity generation from photovoltaic panels was on average 10.5%.

3.4. Electricity consumption and related greenhouse gas emissions

The electricity consumption is summarized in Table 1. The decentralized system consumed 25,207 kWh/month of energy, which amounted to 5% of the total electricity usage on campus. For comparison, a 2002 report stated that 4% of national electricity usage in the USA went towards treating water and wastewater (Goldstein and Smith, 2002). Drinking water treatment used 0.35 kWh/m³ of the locally metered flow. Potable water conveyance to the service centre consumed 0.05 kWh/m³ of flow metered at the drinking water pumping station. Lifting potable water to the water-related facilities and for UV disinfection. The pumps to convey reclaimed wastewater to the point of use for ground water demand used 0.33 kWh/m³ flow metered at the service centre. From the electricity demands, the related carbon emissions could be calculated to illustrate impacts on global warming (Table 1).

3.5. Consumption of chemicals

10 kg/d poly aluminium chloride (PAC) and 0.6 kg/d sodium hypochlorite (NaClO) were used for drinking water treatment (Table 2). Hence, 12.3 g/m³ chemicals were required for wastewater treatment and to provide a disinfection residual in the reclaimed water at a cost of 0.011 £/m³ flow metered at the diameter. The operational costs of the decentralized water system were 35% of the total operational costs in the decentralized system.

3.6. Water infrastructure and operational costs

The rainwater harvesting system accounted for 29% of the water consumption on campus. The operational costs of the decentralized system were 35% of the total operational costs in the decentralized system.
wastewater treated in the decentralized water system investigated in this study was broadly in line with median values reported for centralized drinking and wastewater treatment plants (Table S5 in supporting information). Only a few literature studies have reported measured electricity consumption for modern decentralized water systems. Bhakar et al. (2015) reported the electricity demand for a water system of another higher education campus in India. Their system is distinct from the one investigated in this study, as it relied mostly on groundwater, which was mostly utilized without treatment. Their reported total electricity consumption of 0.40 kWh per person and day (without the electricity demand of groundwater sourcing) can be compared with the 0.34 kWh per person and day total electricity demand of the water system investigated in this study. The electricity consumption of three decentralized wastewater treatment plants investigated by Singh and Kansal was 0.23, 0.25 and 1.86 kWh/m³ (Singh and Kansal, 2018), as compared to 0.62 kWh/m³ in this study. Given this variability, more studies are needed, before the relative electricity consumption of decentralized versus centralized water systems can be reliably established. The chemical consumption of the decentralized water system (Table 2) was very low in comparison with values reported for centralized treatment. For example, UK water companies (2008) reported that chemical usages in centralized drinking water treatment ranged from 4 to 225 g/m³ (76 g/m³ on average), and chemical usages in centralized wastewater treatment from 3 to 240 g/m³ (79 g/m³ on average). The rainwater harvest covered only a small proportion the total demand (Fig. 2a), not only because of seasonal rainfall with a long dry spell from October until May, but also because of the limited roof area per resident in densely occupied and multi-storied buildings like the student hostel. The sustainability of rainwater harvesting systems has also been questioned in regions with more regular rainfall, such as the UK, where operational energy and carbon intensities for a wide range of rainwater applications, including in single family homes, were mostly higher than for conventionally sourced mains water by around 40% (Parkes et al., 2010). Water losses from the decentralized water treatment system (Fig. 3) were high for a newly built system, which was contrary to expectations that the shorter distribution and sewer networks in a decentralized system should minimize leakage. Finally, water quality is another important consideration for the reliability of water infrastructures and will be investigated in more detail in our future work. Preliminary E. coli plate count data (Table S6 in supporting information) suggest that river and rainwater is effectively treated to achieve zero E. coli plate counts in potable water, but many academic households have point-of-use treatment units installed which indicate consumer concerns about potential water contamination during storage and distribution.

### 3.8. Cost benefit analysis for the rainwater harvesting and wastewater reclamation

To evaluate the environmental and economic cost/benefits of rainwater harvesting and wastewater reclamation, the demands for blue water (river water), electricity, and chemicals, and the capital and operational costs of the investigated water system were compared against the base line scenario of a more conventional decentralized water system design. In the baseline scenario, the entire institutional water demand would have been met by river water treated to potable standards. The investigated system delivered notable environmental benefits in terms of reduced river water abstraction (−39%), reduced electricity consumption (−12%), and reduced chemical usage (−30%), as compared to that baseline scenario (Table 4). Reduced blue water abstraction will alleviate water scarcity, which is a significant environmental management challenge in Northwest and Southern India (Katyaini and Barua, 2015). Reduced electricity consumption implies reduced embedded carbon dioxide emissions, as exemplified in Table 1. Addressing the climate emergency is another major environmental management challenge in India, the World’s third-largest carbon emitter (Prakash et al., 2020). Reduced chemical consumption will also reduce embedded carbon dioxide emissions, although these tend to be a small contribution to the overall greenhouse gas emissions of water treatment. For example, a US EPA life cycle assessment of wastewater treatment (Cashman et al., 2014) quoted 12 g CO₂eq per cubic meter of wastewater treated with sodium hypochlorite as disinfectant, which was less than 6% of the overall wastewater treatment impact. However, sodium hypochlorite was accountable for 40% of predicted noncancer human health impacts in the US EPA analysis. Reduced chemical consumption implies reduced road transport of hazardous substances like sodium hypochlorite, which will reduce risks to public health.

Unfortunately, the extra infrastructure capital costs required to achieve these significant environmental benefits of the current decentralized water system were financially unsustainable, as these extra costs could not be recovered through reduced operational costs over a plausible infrastructure lifetime (i.e. the estimated payback period is > 250 years). Given the very high investment demand for expanding water and sanitation infrastructures in low- and middle-income countries, their economic sustainability cannot be disregarded (Reddy and Batchelor, 2011). In addition, the high investment demand for water infrastructure is related to the construction of pipes and tanks from materials with embedded environmental impacts. It has already been reported that rainwater harvesting has a larger carbon footprint than conventional water supply when considering both operational and embedded carbon emissions (Way et al., 2010). While a full life cycle environmental impact assessment is beyond the scope of the current study, it is desirable to minimize all four of the primary parameters considered in this study (i.e. the direct consumption of blue water, electricity, chemicals, and costs). The analysis of additional scenarios demonstrated how, without the rainwater harvesting infrastructure, and also without those reclaimed wastewater infrastructure components only needed when reclaimed water actually were to be used for toilet flushing, a slimmed-down version could have achieved reductions in blue water, electricity and chemical consumption similar to the current system, but with significantly lower capital costs and a payback time of only 15 years. Wastewater reclamation for ground maintenance only would therefore appear to be a truly sustainable technology for low- and middle-income countries, achieving both, environmental benefits and financial economies.

### Table 4

|                  | Conventional, 100% blue water treated to potable standards | Current system, and difference to conventional | Rainwater harvesting only, and difference to conventional | Wastewater reclamation for ground maintenance only, and difference to conventional |
|------------------|----------------------------------------------------------|----------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------------------------|
| Blue water volume (m³/year) | 379,768                                                   | 232,537 < 39%                               | 354,566 < 7%                                            | 257,739 < 32%                                                                      |
| Electricity (kWh/year)       | 343,776                                                   | 302,480 < 12%                               | 343,776 0%                                             | 302,480 < 12%                                                                      |
| Chemicals (t/year)           | 5.7                                                       | 4.0 < 30%                                   | 5.7 0%                                                  | 4.0 < 30%                                                                         |
| Capital costs (£)            | 2,039,249                                                  | 3,525,540 73%                               | 3,073,340 51%                                          | 2,259,916 11%                                                                      |
| Operational costs (£/year)   | 115,006                                                   | 93,564 < 19%                                | 111,941 < 3%                                           | 96,628 < 16%                                                                       |
| Payback period (years)       | > 250                                                     | > 250                                       | > 250                                                   | 15                                                                              |

Journal of Environmental Management xxx (xxxx) xxx
The system investigated was not operating as originally designed, mainly because the volume of reclaimed water was insufficient to meet both, ground maintenance and toilet flushing demands, because of water losses from the system. Since it was not certain, how and where exactly these significant water losses occurred, two scenarios were developed for a loss-free system, based on the assumption that a) the main water loss occurred from the potable water distribution system, or b) from the sewer. These scenarios showed how the environmental and economic performance of the system could be substantially enhanced by preventing and/or addressing losses that presumably were mainly due to leakage (Table 5). In the case of wastewater leakage from the sewer, the electricity demand of the system would increase, but only because all the wastewater generated would then be treated rather than partially released into the environment without treatment due to leakage from the sewer. We also calculated that a drought-resilient landscaping strategy would yield very substantial environmental and cost benefits by freeing up more reclaimed water for the flushing of toilets.

### 5. Conclusions

Our real-world study supported the technical feasibility, environmental and economic benefits of maximizing the use of local water resources through wastewater reclamation and reuse for ground maintenance and irrigation with zero discharge. Such as system could help protect blue water resources (surface water and groundwater) in a semi-arid region of India, with a realistic payback time for the required infrastructure investments through reduced operational costs. On the other hand, rainwater harvesting, which is currently being promoted by Indian government policies, was found to have very high investment costs for more limited environmental benefits. Hence, it is recommended that future water policies should promote wastewater reclamation for non-potable reuse where there is a high local water demand for ground maintenance. These findings were dependent on the local climatic conditions in a hot, semi-arid region of India with a summer, monsoon and winter season. Other scenarios can be readily developed from our case study data, for example rainwater volumes harvested from the roof area for a higher annual precipitation scenario would simply increase proportionally to this difference in the annual precipitation. Our study showed how significant gaps existed between the original water system design, and its real-world operations, which demonstrated the need for more ground-truthing to assess the viability of innovative water infrastructure ideas. Our study also illustrated how the growing water demand of more affluent consumers in a middle-income country, such as the academic households in this study, can negate any gains achieved through innovative water supply and reuse technologies. Water policy should therefore also focus on promoting measures to address this raising demand through reduced leakage, drought-tolerant landscaping, reduced potable water use for ground cleaning, ultra-low water use appliances, water user education, and financial incentives such as volumetric end user charges, to secure the gains achieved with innovative water infrastructures.

### 3.9. Water management optimization opportunities

Optimization opportunities for the management of the current system.

| Current | Without water losses, if current losses are mainly due to potable water leakage, and difference to the current situation | Without water losses, if current losses are mainly due to wastewater leakage, and difference to the current situation | With drought resilient landscaping, and difference to the current situation |
|---------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Blue water volume (m³/year) | 232,537 | 112,346 | 52% | 164,682 | −29% | 145,586 | −37% |
| Electricity (kWh/year) | 302,480 | 200,946 | 34% | 318,092 | 5% | 262,097 | 13% |
| Chemicals (t/year) | 4.0 | 2.2 | 45% | 3.0 | 24% | 2.7 | −33% |
| Operational costs (£/year) | 93,564 | 71,801 | 23% | 85,424 | 9% | 79,601 | −15% |

### CRediT author statement

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### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

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