Assessment of the potential contribution of alternative water supply systems in two contrasting locations: Lilongwe, Malawi and Sharm El-Sheikh, Egypt

Osman Jussah, Mohamed O. M. Orabi, Janez Sušnik, Françoise Bichai and Chris Zevenbergen

ABSTRACT

Growing water demand poses a challenge for supply. Poor understanding of alternative sources can hamper plans for addressing water scarcity and supply resilience. The potential of three alternative supply systems in Lilongwe, Malawi and Sharm El-Sheikh, Egypt are compared using a fast, data-light assessment approach. Lilongwe water supply is based on unsustainable use of source water, while Sharm depends primarily on desalination. Both locations experience shortages due to poor system performance and service inequity. Alternative supply systems are shown to potentially contribute to supply augmentation/diversification, improving service and system resilience. There are considerable seasonal variations to consider, especially regarding storage of water. Social preferences could limit the uptake/demand for alternative water. One important conclusion is the value in addressing public perceptions of alternative systems, and assessing water end use in order to site systems appropriately. Other issues surround financing, encouraging uptake and addressing institutional/governance aspects surrounding equitable distribution. A further consideration is whether demand reductions might yield shorter-term improvements in performance without the need to institute potentially expensive alternative water strategies. Reducing non-revenue water is a priority. Such measures should be undertaken with alternative supply enhancement to reduce inequity of supply, improve system performance and increase resilience to future changes.

Key words | alternative water supply sources, rainwater harvesting, stormwater harvesting, urban water management, water security

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INTRODUCTION

Urbanisation is expanding rapidly and the urban population is anticipated to increase from 54% to 66% of global population by 2050 (UN-DESA 2015). Growing urban populations are stressing water services, evidenced by many water providers being challenged by rapidly growing demand (Chidya *et al.* 2016). Many cities face problems on how to secure water for their population (Loáiciga 2014; McDonald *et al.* 2014). Water demand in urban areas could increase up to 92% compared with the present time (World Bank 2009) due to population growth and changing socio-economic conditions (Dzidic & Green 2012).

On the other hand, freshwater supply is being affected by changing rainfall patterns, the need to secure water for ecosystem functioning and competing users. Due to increasing stress on traditional water resources, many countries invest in alternative water supply sources (AWSs) to augment conventional water sources. Commonly used alternative sources are desalinated water, treated

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wastewater, captured stormwater and harvested rainwater (Agudelo-Vera *et al.* 2013). Alternative water sources can play an important role to close the supply–demand gap and can reduce the stress on existing sources (Agudelo-Vera *et al.* 2013). Although AWSs face public and cultural reluctance regarding drinking purposes and public health, they can be treated to drinking quality. They play a strong role in non-potable uses that do not require high quality of water, such as irrigation of municipal parks, open spaces and urban agriculture (Hardy *et al.* 2015). AWSs also have the potential to increase water supply system resilience by increasing the diversity of supply options (Bichai *et al.* 2015).

In analysing the contribution of potential alternative sources, decentralised approaches (Leusbrock *et al.* 2015) and different water end-uses are considered in order to explore the demand for and feasibility of using different alternative water sources (Agudelo-Vera *et al.* 2013). Alternative sources are assessed on a number of variables, such as the quantity and quality of water provided, and the temporal and spatial availability (Leduc *et al.* 2009; Panagopoulos *et al.* 2012; Bichai *et al.* 2015). Other factors that are also considered when assessing AWSs are social and cultural acceptance issues, the technical and financial feasibility of different systems, hydrological and climatological considerations, storage, treatment and distribution options, and user affordability (Sturm *et al.* 2009). While keeping in mind the factors which affect use of alternative water supply, Agudelo-Vera *et al.* (2013) showed that up to 70% of urban water use does not require drinking quality water. These uses represent opportunities for AWSs to contribute to water supply security by supplementing drinking-quality water with other water to be used for non-potable purposes.

Rainwater and stormwater harvesting systems (rainwater harvesting (RWH) and stormwater harvesting (SWH), respectively) as well as wastewater reuse have been explored and implemented in many settings. Studies have assessed the potential volumetric contribution, different opportunities and challenges, and social and political factors related to these systems. Regarding RWH, a building-scale case study in the Netherlands found that RWH can supply considerable volumes of water (up to 80% of demand; Agudelo-Vera *et al.* 2013). Major barriers were available rainfall, temporal changes in rainfall and adequate on-site storage. Also at the building scale, Yan *et al.* (2018) show that when coupled to a point-of-use treatment facility, harvested rainwater covered anywhere from 0.6 to 100% of the demand, the variability reflecting significant seasonal rainfall variation. On a regional level, dos Santos *et al.* (2017) indicate that in northeast Brazil, a semi-arid region, rainwater stored in large tanks could save up to 25% of water from the public network, which currently serves 60% of people. On a national level, Lee *et al.* (2016) show that while Malaysia has significant RWH potential and has been proposed by the government as a water augmentation strategy, there are a number of challenges to nationwide implementation including environmental factors, policy issues, economic and social considerations, and technical constraints, especially regarding current system losses and storage. Campisano *et al.* (2017) show that while rainwater system implementation is expanding in Africa generally, a lack of infrastructure to store, treat and distribute water is hampering wider uptake.

Regarding stormwater, Clark *et al.* (2015), in a study in South Australia, show that SWH systems for managed aquifer recovery could offer up to nearly 13% of annual demand based on historic rainfall data, while future rainfall reductions lead to a 3% decrease in supply. Increasing impermeable areas could lead to large supply increases. Saraswat *et al.* (2016) offer an overview of stormwater management practices in Bangkok, Hanoi and Tokyo. All three cities employ some sort of stormwater management and harvesting systems, with stored water (sometimes in considerable volumes) being used for subsequent applications. Exact typologies of the systems differ according to local conditions and requirements. Assessing three full-scale SWH systems in Melbourne, Australia, Petterson *et al.* (2016) show that water yield varies strongly by design. The designs yielded from 33 to 78% of demand at the different locations, indicating the efficacy of appropriately designed and implemented systems. As part of suitable design, adequate water storage capacity and treatment are required.

Regarding wastewater, a study of cases from three water-scarce countries with distinct political economies – Australia, the United Arab Emirates (U.A.E.) and Jordan – highlights key barriers occurring within the sophisticated but fragmented institutions that regulate wastewater reuse in Australia, while in the U.A.E., although agricultural reuse is widespread, policy-induced path dependency hinders wider uptake of this option (Bichai *et al.* 2018). In comparison, Jordan faces a wider infrastructural and institutional gap, which may actually imply less stringent barriers to wastewater reuse developments within its innovation system, namely, influenced by international donors.

While there are many studies of AWSs, few consider a range of options at city level. Among those, the Alternative Water Atlas, based on spatial multi-criteria analysis of alternative water supply options and demand, revealed that the combined potential of the sources under study (rainwater, stormwater, wastewater) would likely outstrip the projected demand for non-potable uses over the next decades in Melbourne, a city affected by drought (Bichai *et al.* 2015). Yet, in cities of the Global South facing water security challenges, there remains a paucity of data and assessments available to support decision-making on alternative water supply strategies.

This study, exploring the potential of AWSs, was carried out in in two contrasting cities in terms of population, water uses and climate. Nevertheless, both are experiencing water shortages in the public network. First, Lilongwe City, Malawi is challenged by the lack of sufficient water supply resources in the public network to meet the increasing water demand (Chidya *et al.* 2016), a high urban growth rate and largenon-revenue water (NRW) losses. Second, Sharm El-Sheikh, Egypt relies largely on desalinated water because traditional water sources do not exist locally in any appreciable volume. Water provision is the responsibility of public and private sectors in Sharm. Water is not equally distributed among users. This study helps to fill a critical gap in the understanding on potential alternative water supply systems at city level, which could help to meet water demand, thereby contributing to the literature on alternative urban water supply systems, especially in the context of cities in developing countries.

The aim of this paper is to compare the current and potential future water supply and demand situations in the two case study cities, and to assess the potential contribution of various alternative water supply systems, such as wastewater reuse and rainwater/stormwater harvesting, to boosting water supply resilience and security. Seasonal variations are accounted for. Potential public perception and acceptance issues are also addressed. The unique characteristics of each site are considered, and the opportunities and challenges of implementation are discussed. The results and findings add first-order local-scale assessment of the possible benefits of alternative water supply systems in the two different cases, which both suffer from water supply shortages and insecurity for different reasons. A relatively simple, fast and resource/data-light methodology is adopted to give first-order estimates of the potential of alternative water supply systems. Such an approach may prove beneficial, especially in developing nations/cities who may lack the up-front resources for more sophisticated investigations. This high-level assessment focuses on quantitative aspects of resources availability for potential supply. It is recognised that water quality is a key consideration in developing alternative sources that require a detailed risk-based approach to ensure public safety, something which is not covered in this study. Here, the potential of alternative sources to contributing to bridging the water supply–demand gap is evaluated. The underlying assumption is that for this potential contribution to be harnessed, one essential condition would be that adequate treatment processes, monitoring and controls be in place to ensure public health safety at end use.

STUDY SITES

Lilongwe, Malawi

Lilongwe (Figure 1(a)) has an average annual temperature and rainfall of 21 °C and 852 mm (2003–2012 averages), respectively, with a rainy season between November and April. In 2008, the population was 674,448, with an average annual growth from 1998 to 2008 of 4.3% (National Statistical Office 2012). The city area is 328 km^2, and had a population density of 1,479 people/km^{-2} in 2008. The city has many zones defined by housing density (low, medium and high density zones) and industrial zones. The higher density housing zones correlate with medium and lower incomes and vice versa (UN-HABITAT 2011).

Water supply in Lilongwe is managed by the Lilongwe Water Board (LWB; as stipulated by Malawian legislation). In recent years, demand has not been met due to supply constraints (Chidya *et al.* 2016) and poor network performance.

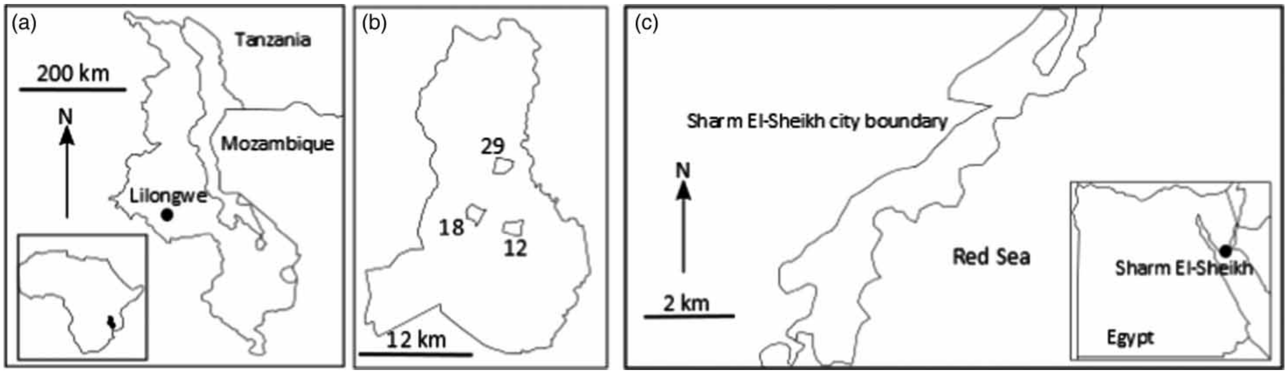

Figure 1 | (a) The location of Lilongwe (Malawi). (b) The Lilongwe city boundary, highlighting Zones 12, 18 and 29. Kauma lies just outside the city boundary to the north-east (not marked on the map). (c) The location of Sharm El-Sheikh, Egypt.

Water is currently supplied to about 70% of city residents. Many supplied residents may not receive water for 24 hours a day. In the city, there is growing stress on traditional river and groundwater sources, both of which are over-exploited. Water quality of the raw water is an increasing concern, and energy constraints lead to power cuts, with implications on water supply continuity and treatment. As a result, (partially decentralised) alternative water sources are being considered as a way to boost supply and diversify supply options, and to reduce the burden on the power sector.

In this study, four city zones are considered. The zones are: Zones 12, 18, 29 and Kauma (Figure 1(b)). These zones were chosen because they represent a good cross section of Lilongwe area typologies, are well planned, and have functioning water supply and wastewater systems. For these reasons, they could be used as potential rollout sites using results from studies such as this.

Sharm El-Sheikh, Egypt

Sharm El-Sheikh (hereafter 'Sharm') contrasts starkly with Lilongwe. Sharm (Figure 1(c)) lies at the southern tip of the Sinai Peninsula on the Red Sea at the mouth of the Al Aqaba Gulf to the east and the El Suez Gulf to the west (Borhan *et al.* 2003). Sharm is one of the driest cities in the world, receiving 20–50 mm rainfall per year. As a result, Sharm relies heavily on desalinated water and on long-distance water transfers from an overexploited aquifer near the city of Al-Tor, 100 km to the north. Treated wastewater is used for irrigation of golf courses and municipal vegetation. Sharm has a population of 83,973 according to the 2009 census (UNISDR 2011). It has an annual population growth rate of 3.8% (Lamei *et al.* 2009a). For this study, the whole city was considered.

Tourism is the dominant economic activity in Sharm, despite having endured a recent slump (from 4.5 million visitors in 2010 to 1.5 million in 2016; ETA 2016 Personal communication with Islam Nabil, information department, Sharm El-Sheikh office, Egyptian Tourism Authority. November 2016). Tourist water demand, accounting for about 90% of total water demand (Lamei *et al.* 2009b) and increasing residential water demand is putting considerable pressure on the scarce resources. In 2010, total water shortage was estimated to be $3 \times 10^6\ \text{m}^3\ \text{yr}^{-1}$ (Lamei *et al.* 2008), which is exacerbated by(NRW in the public supply of around 40% (Omar, H. 2016 Personal communication with Hanan Omar, Director of Sharm El-Shiekh region, North and South Sinai Company for Water and Wastewater, Egypt). Public water in Sharm is supplied by the North and South Sinai Company for Water and Wastewater (NSSCWW); however, there are many bodies responsible for providing water to different sectors in Sharm, each of which has access to different water sources (Lamei *et al.* 2009c). For example, many hotels are provided with desalinated water via contracts with private operators for fixed water volumes irrespective of actual demand.

In both locations, alternative water sources are either being used (Sharm) or being considered (both) in order to: i) enhance the security of supply, especially for non-potable uses which quite often do not demand drinking-quality water; ii) diversify supply options, enhancing resilience to future changes; iii) free up scarce resources for drinking water supply, reducing the pressure on these resources.

As well as boosting supply, both cities are acutely aware of the need for water demand management. Per-capita consumption is high, andNRW is high in both locations, but the nature of the NRW (i.e., physical loss or commercial loss) is not well known in either location. While demand-side management is acknowledged as an important component of urban water supply and security planning, this paper focuses on the contribution of AWSs to boost and diversify supply, providing additional options to urban planners, and potentially aiding an increase in urban water supply resilience.

DATA AND METHODS

The study is concerned with the assessment of the *potential* contribution from three AWSs: RWH, stormwater harvesting, and wastewater treatment and reuse. It is understood that *actual* volumes of harvested water are likely to be considerably lower than potentials due to factors such as financing, governance and political will, user acceptance and demand for alternative water. However, determining how these factors may influence uptake of any potential system is highly uncertain, and the factors can change in very short time scales. The aim throughout this study was to estimate potentials as a preliminary assessment of supply augmentation possibilities to address or prevent future water shortages in both cities. Current and potential future conditions in 2030 are assessed. This section describes the steps taken to arrive at potential volumes from each of the three systems, and the data used.

Data common between the case studies

Climate data for the present day and for future scenarios was collected from the World Bank Climate Change Knowledge Portal (http://sdwebx.worldbank.org/climateportal/). Average monthly historical climate data (1991–2015) are available at each location for the period 1991–2015 from the Portal. Future projections in the World Bank dataset are taken from the Coupled Model Intercomparison Project 5th Phase project (CMIP5; Taylor *et al.* 2012). In this paper, the results for the timeslice 2020–2039 were used, as the future scenario in this work is set at the year 2030, a reasonable mid-term planning horizon. The complete suite of model results from the CMIP5 project are available and were downloaded. These datasets are globally recognised, and frequently used in academic studies across disciplines.

Spatial data were derived from common sources. These included extraction of rooftop area and study site area for rainwater and stormwater harvesting analysis, respectively. Rooftops are embedded as an individual layer within the OpenStreetMap (OSM) website (http://www.openstreetmap.org). Because OSM is open-source and regularly updated, it is generally up-to-date although this does vary considerably by location, and it is updated more frequently and accurately than other mapping services. Intimate local knowledge of the study areas by two of the authors (OJ and MOMO) verified the accuracy of the datasets. In addition, the OSM data were cross-checked both against the latest available satellite imagery of the study areas and during field visits conducted to the study sites (i.e., the data were triangulated across observational methods). The OSM data were verified as accurate and up-to-date.

Data unique to each case study

In addition to common data, unique data were required in order to capture the specificities of each location. Unique information includes:

- Current statistics on the water systems, and water supply and demand, including where possible information on NRW: This information was collected locally from the relevant local authorities (e.g., LWB, North and South Sinai Company for Water and Wastewater (NSSCWW), private desalination operators, hotels) during field visits in December 2016. As these data on local water supply and demand come primarily from relevant water authorities, producers and users, it is assumed that the data are as accurate and reliable as possible for the respective study locations.
- Information on water users: This was obtained partly through local water authorities and through questionnaires conducted with members of the public during December 2016.
- Information on tourism sector water demand, where applicable (i.e., for Sharm): This information was

collected from local and national statistics and plans, from the literature, and from local hotel operators in December 2016.
- Data on public acceptance regarding the uptake and use of water from various alternative water sources: This information was gathered from questionnaires carried out *in situ* with staff from local water companies and with members of the public in December 2016.
- Information on potential institutional challenges in the current and potential future water system was collected through interviews and questionnaires with water authority staff.

Interviews with members of the public, hoteliers and water authority staff were conducted in a semi-structured format. A standard questionnaire, tailored for each stakeholder group, guided the interviews. However, many respondents also added their own perspectives, expertise and opinions around the topic and the questions being asked.

For the stormwater harvesting analysis (see below), soil types and land use and land cover (LULC) maps were acquired. Soil data for Sharm were collected from the European Soil Data Centre (ESDC; Jones *et al.* 2013). The LULC maps for Sharm were obtained from the Harvard Map Collection and Harvard College Library spatial data repository (NYU 2017). In Lilongwe, the soil maps were sourced from the Department of Lands, while the LULC map was sourced from Land Resource Conservation Department. These open-access online resources were used as part of the effort put forth in this study to provide alternative assessment methodologies to intensive local data requirements, where such data are lacking. These datasets are used as the best available estimates for a first-level assessment; however, cross-validation with locally sourced data is precluded.

Assessment of the current water system and of suitable alternative water supply systems typologies

Because of the stark contrast between the study sites, there are differences in the type of AWSs that are feasible and/or desirable. In order to assess the likely system typologies in each area, local staff in water authorities were interviewed for their opinions on potentially useful AWS types. The semi-structured interviews were used to collect basic data on the setup of the existing water system. In Lilongwe, interviews were carried out with operational staff from LWB, while in Sharm, interviews were carried out with operational and managerial staff from NSSCWW, hotel personnel, the Ministry of Water Resources and Irrigation and the Water Resources Research Institute. In both cases, rainwater and stormwater harvesting were considered as possible sources, while in Lilongwe the collection, treatment and reuse of wastewater was also deemed a possible additional source of water. In Sharm, while wastewater is being used for non-food crop irrigation, it was not expected to be expanded upon in the near future. Therefore, the assessment in Sharm focuses on rain-based sources (i.e., RWH and collection of stormwater during infrequent but intense flash floods).

Estimation of potential contribution from rainwater harvesting

The potential of RWH was assessed using a consistent methodological approach for both case studies. By RWH, we refer to rainfall that is captured, stored and used from rooftops. To estimate the potential volume from RWH in the study areas, rainfall data and rooftop area were required, along with information on rooftop collecting efficiencies. Rainfall data were sourced from the World Bank Climate Knowledge Portal, and the rooftop area was calculated from the layer extracted from OSM (see above). The potential RWH volume can be estimated with:

$$V_{RWH} = RxAxC/1000 \tag{1}$$

where V_{RWH} is the volume potential from RWH, R is the rainfall depth (monthly or annual, m), A is the rooftop surface area (m^2) and C is rooftop runoff coefficient. Abdulla & Al-Shareef (2009) estimated that 20% of rainfall onto rooftops evaporates in Jordan, and Aladenola *et al.* (2010) considered a rainwater collection efficiency of 85% in Nigeria. Due to the similar climatic settings and building material in Sharm and Lilongwe, the same value as in Abdulla & Al-Shareef (2009; 0.8) was used. For 'water saving' types of system, which are simpler and which are considered here, a commonly used guide for the tank size/collected volume is 5% of annual demand or annual yield (whichever is smaller; Kellagher & Andres 2015). It is pointed out, that in a few cases, certain buildings were not suitable for RWH. For example, in Sharm, some buildings have roofs constructed from straw, and are not well suited for RWH system installation. Such buildings were identified on the ground during field visits and removed from the analyses.

It is acknowledged that the assessment approach does not account for rainfall variability. Due to resource limitations, especially regarding historical climate data, this work only had access to historical monthly average rainfall values. Local rainfall data were not available, and characterisation of variability was not possible, prohibiting a more sophisticated stochastic approach. A benefit of this method is however that it allows for fast, first-order estimates of RWH potential in data-scarce areas, which could be beneficial to many developing regions globally. Here, we develop a simplistic approach for preliminary assessment of the *potential* contribution of alternative sources under potential future climate scenarios (that incorporate uncertainty). This is beneficial for water sector agencies that may request initial high-level assessment of options to enhance urban water security. The simple methodology helps meet an initial need to raise awareness on the potential of under-exploited sources that can contribute to bridging water supply and demand gaps in water stressed cities. Once suitable options are identified based on initial estimates, resources for further investigation may be made available. Through the use of the CMIP5 climate projection data suite, average and 10th and 90th percentile changes in RWH can be estimated for future conditions in 2030 in both study areas.

Estimation of potential contribution from stormwater harvesting

In this study, the Soil Conservation Service-Curve Number method (SCS-CN; Gajbhiye 2015) was used for the relative simplicity of data requirements. In order to estimate the potential stormwater volume from rainfall runoff, the following sets of equations are used:

$$CN = \frac{\sum(CNi \times Ai)}{A} \tag{2}$$

where CN is the weighted curve number, CNi is the curve number for each hydrologic soil group (HSG; UDA 1986) from i to n, Ai is the area of each HSG (m^2) and A is the total study area (m^2). For each study site, the HSG classification and the value for CNi was based on the soils maps and comparing this with the classification scheme in USDA (1986).

The results of the CN calculation above are used to estimate maximum recharge potentials, and subsequently the potential stormwater runoff. To estimate potential recharge values, the following is used (Gajbhiye 2015):

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where S is the maximum potential retention and CN is calculated from Equation (2). Finally, potential stormwater runoff volume can be estimated from:

$$Q = \frac{(P - 0.3S)^2}{(P - 0.7)} \tag{4}$$

where Q is the runoff (m^3 s^{-1}), and P is the precipitation (m s^{-1}).

In order to avoid double-counting of volumes, the potential volume falling on rooftops is deducted from these totals.

Estimation of potential contribution from treating and re-using wastewater

The consideration of reusing treated wastewater was applied only in Lilongwe. Two approaches were compared. The first approach was based on wastewater volumes generated from current supply volumes. In order to estimate the amount of wastewater generated, the amount of water supplied is multiplied by the percentage of wastewater generated in each zone as provided by the LWB (LCC 2010). This percentage represents the non-consumptive water uses in the city. This percentage differs in each of the four Lilongwe city areas. In Zone 12, the percentage of supply volume that goes to wastewater treatment is 75%, in Zone 18 it is 80%, in Zone 29 it is 80% and in Kauma it is 90%. It is assumed that this wastewater is then available for treatment and reuse.

The second approach is based on water demand, and assumes that the full demand is met, or may at some future time be met, by supply. This analysis was undertaken to estimate the change in potential wastewater for reuse should demand be fully met. The demand totals in each area were also scaled by the wastewater delivery ratios stated above. For SWH and treated wastewater, water system efficiencies are used to scale calculated values. All values presented here are system efficiency corrected values.

RESULTS

Current water supply and demand

In Lilongwe, water is supplied from nearby surface and groundwater sources. Water supply trends show that most water is supplied to the industrial area (Zone 29) followed by residential Zone 18, 12 and lastly Kauma, a low income area (Figure 2(a)). Per-capita water demand is highest in Zone 12 (high income), followed by Zone 18 (medium income) and Kauma. Analysis shows demand trends similar to that of supply (Figure 2(a)). Analysis of monthly data shows relatively little variation in demand through the year (average of monthly demand from 2007 to 2015).

Baseline water supply and demand analysis shows water deficit in all four city zones (Figure 2(a)). Monthly average water deficit is lowest in industrial Zone 29 (21%), and ranges from 38% (Zone 18) to 52% (Zone 12 and Kauma) in residential areas. Higher levels of water deficit are observed in the months of February, March, April and May due to lower water supply at the end of the dry

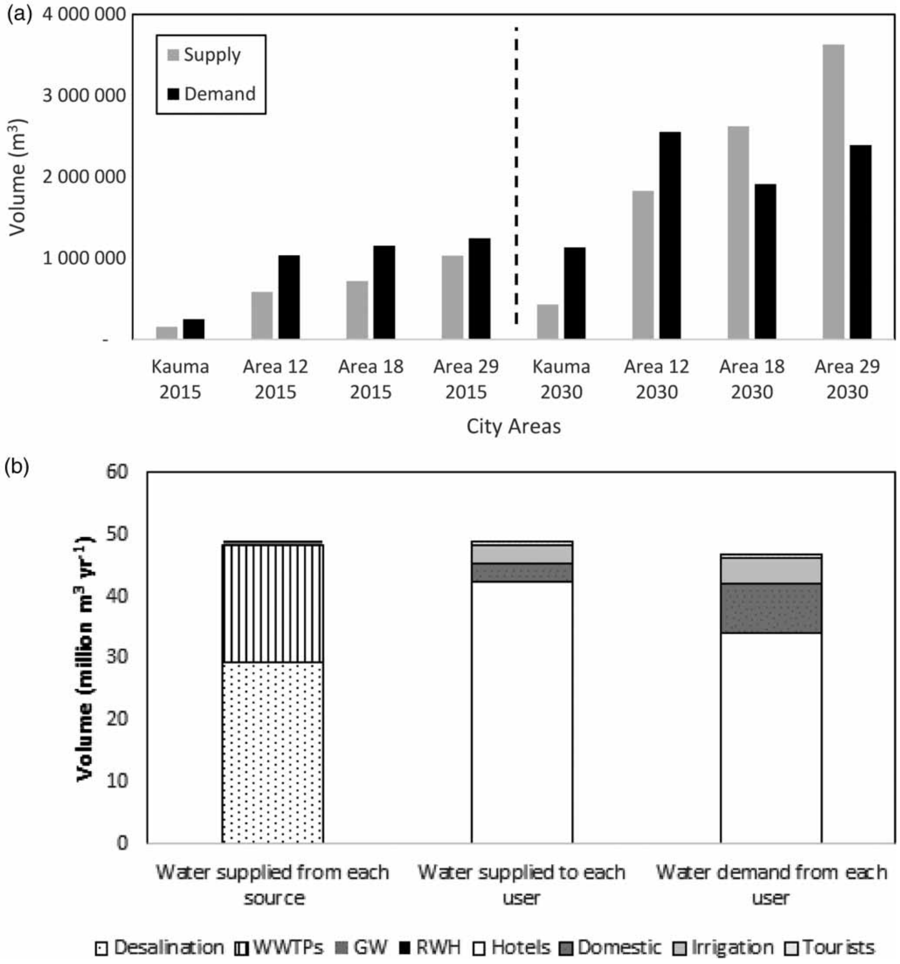

Figure 2 | (a) Current (2015, left of dashed line) and future projected (2030, right of dashed line) annual water supply and demand graph in each of the four Lilongwe city areas. (b) Current water supply and demand in Sharm El-Sheikh. WWTPs, wastewater treatment plants; GW, groundwater; RWH, rainwater harvesting.

season. At present, the total water supplied to the four study areas in Lilongwe is *c.* 2.5 million m^3 yr^{-1}, however current demand is estimated at *c.* 3.7 million m^3 yr^{-1}.

In Sharm, desalination of seawater forms the dominant freshwater supply source. Wastewater treatment and reuse and a small contribution of groundwater imported from Al-Tor city contribute the remainder of the freshwater supply. Desalination, wastewater reuse and groundwater imports contributed 29.38, 18.98 and 0.36 million m^3 yr^{-1} in 2016 (Figure 2(b)).

Five companies dominate the desalination market. There are ten centralised and about 60 smaller decentralised desalination plants in operation with a total capacity of *c.* 80,500 m^3 day^{-1}. Treated wastewater is used for two main purposes: 1) to irrigate green and open spaces such as municipal parks and gardens; 2) to dilute effluents discharged to water bodies as a pollution mitigation measure. About 90% of hotels in Sharm have their own wastewater treatment plant. Five municipal plants are operated in the city. In 2016, *c.* 52,000 m^3 day^{-1} of treated wastewater was being produced.

Nomads, who live on the city outskirts (Omar, H. 2016 Personal communication with Hanan Omar, Director of Sharm El-Shiekh region, North and South Sinai Company for Water and Wastewater, Egypt), and who are not formal city dwellers, use traditional methods to capture and harvest the scant rainwater resources for drinking and cooking purposes, contributing a negligible volume (*c.* 0.0007 million m^3 yr^{-1}) to overall water supply. This is occasionally supplemented with the purchase of 100 litres of water delivered by tanker which supplies ten people for up to 5 days (Omar, H. 2016 Personal communication with Hanan Omar, Director of Sharm El-Shiekh region, North and South Sinai Company for Water and Wastewater, Egypt).

Domestic water is supplied by NSSCWW through a network with about 3,000 connections. Local water consumption is estimated to be *c.* 150 L cap^{-1} day^{-1}, but actual consumption may be as high as 250 L cap^{-1} day^{-1} if not higher due to network losses (Omar, H. 2016 Personal communication with Hanan Omar, Director of Sharm El-Shiekh region, North and South Sinai Company for Water and Wastewater, Egypt). Irrigation demand is largely a function of plant/crop type and area irrigated; however, water price, system efficiency and soil and climate types are also important variables (Gössling *et al.* 2012). The current irrigated demand in Sharm includes two 18-hole golf courses, as well as woodland plantations and municipal gardens.

In terms of water demand in Sharm, tourism is by far the largest water demanding sector (Figure 2(b)). Sharm has over 185 hotels with an estimated 55,500 rooms (ETA 2016 Personal communication with Islam Nabil, information department, Sharm El-Sheikh office, Egyptian Tourism Authority. November 2016). Water consumption per room ranges from 1.5 to 2 m^3 day^{-1} (GATD 2016 Personal communication with Ahmed Hassan, Director of Sharm El-Sheikh office, General Authority for Tourism Development). In 2016, the average hotel occupancy rate was 20% (GATD 2016 Personal communication with Ahmed Hassan, Director of Sharm El-Sheikh office, General Authority for Tourism Development). Each tourist is estimated to use 0.3 to 0.5 m^3 day^{-1} for washing, showering and catering (Gomes, A. 2016 Personal communication with Artur Gomes manager of operation and maintenance in Jollie Ville Resort Casino, Sharm El-Sheikh.) Domestic use and irrigation make up the remainder of the demand, but are very small in volumetric terms. Currently, the total water demand of Sharm is estimated at 46.94 million m^3 yr^{-1} divided into 7.76, 34.17, 0.60 and 4.41 million m^3 yr^{-1} from domestic, hotels, tourists and irrigation water demand, respectively (Figure 2(b)).

The total supply in Sharm of about 48.73 million m^3 yr^{-1} (2016), is inequitably distributed. While the hotel sector has a volumetric water surplus of *c.* 8.11 million m^3 yr^{-1}, the domestic and irrigation sectors experience shortages of 4.65 and 1.68 million m^3 yr^{-1}, respectively (Figure 2(b)).

Potential changes to water supply and demand by 2030

Potential changes to water supply in Lilongwe were projected for the year 2030 based on Water Board projects and plans to increase water supply in the city. In Lilongwe, the Lake Malawi and Diamphwe water supply projects have the potential to supply an additional capacity of 80,000 m^3 day^{-1}, bringing the total supply capacity to 205,000 m^3 day^{-1}. Projected water supply to the city zones by 2030 was based on the current trend of water supply volumes (Jussah 2017). Potential changes to water demand in the city zones by 2030 was computed based on the projected population growth rate, and the projected water consumption for each city area.

In Lilongwe, assuming that current water supply and demand patterns persist until 2030, then in terms of supply, Zone 29 is projected to receive the most water while low-income Kauma is projected to receive the lowest from the water board. On the other hand, the water demand in 2030 is estimated to be highest in high-income Zone 12, followed by Zone 29, Zone 18 and lastly Kauma (Figure 2(a), right of dashed line). In 2030, a water deficit in Kauma of up to 62% is expected, while Zone 12 will suffer a deficit of 28%. Conversely, Zones 18 and 29 are projected to be satisfied with supply if the current trend of water supply increase continues. The results highlight the expected continuation of inequitable water supply distribution within the city.

In Sharm, based on the analysis of the existing water system, the main assumptions behind assessment of possible changes to 2030 are (Omar, H. 2016 Personal communication with Hanan Omar, Director of Sharm El-Shiekh region, North and South Sinai Company for Water and Wastewater, Egypt): a) the sectors that will require water in 2030 are the same as current activities; b) water consumption rates will not change; c) the water supply of harvested rainwater and groundwater will not change; and d) water demand from hotels and irrigation remain constant due to no known plans for the tourism sector's expansion in terms of constructing new hotels and touristic districts over the intervening years (ETA 2016 Personal communication with Islam Nabil, information department, Sharm El-Sheikh office, Egyptian Tourism Authority. November 2016).

In terms of anticipated water supply by 2030, NSSCWW is planning to operate a new desalination plant with design capacity of 12,000 m^3 day^{-1} by the end of 2017. Private water companies are expecting an increase of 10% (7,250 m^3 day^{-1}) in their existing operating capacity due to an anticipated increase in demand by 2030. NSSCWW aims to reduce the 40% NRW to 20% by 2020 through network upgrades, leading to a potential increase in supply (through loss reduction) of 8,600 m^3 day^{-1}. This potential increase of water supply by NSSCWW from desalination and loss reduction would increase the volume of delivered wastewater by 6,880 m^3 day^{-1}. As such, the volume of treated wastewater is expected to increase by *c.* 4,100 m^3 day^{-1}, accounting for current treatment efficiencies in the plants. Consequently, the possible increase in the existing water supply by 2030 is estimated as 15,850 and 7,600 m^3 day^{-1} from the desalination system and wastewater treatment system, respectively.

In terms of demand, the number of tourists is anticipated to increase by 14% in Sharm by 2030 (ETA 2016 Personal communication with Islam Nabil, information department, Sharm El-Sheikh office, Egyptian Tourism Authority. November 2016). As a result, water demand of the tourist sector is predicted to increase to 11,640 m^3 day^{-1}. The water demand of local inhabitants is anticipated to increase to 36,100 m^3 day^{-1} by 2030 due to a population growth rate of 3.8% (Lamei *et al.* 2009a, 2009b, 2009c). In total, water demand in Sharm is predicted to increase to 153,500 m^3 day^{-1} by 2030.

It is projected that the local population will continue facing shortage. The gap between water supply and demand of domestic residents will increase to 6.75 million m^3 yr^{-1} by 2030 (Figure 3). In contrast, water demand for irrigation will decrease to 0.17 million m^3 yr^{-1} due to the predicted increase in treated wastewater for irrigation. The tourist sector is anticipated to achieve a surplus of 8.40 million m^3 yr^{-1} by 2030. In total, the potential water supply will exceed the anticipated water demand by 2030 (Figure 3), but may be even more inequitably distributed than present.

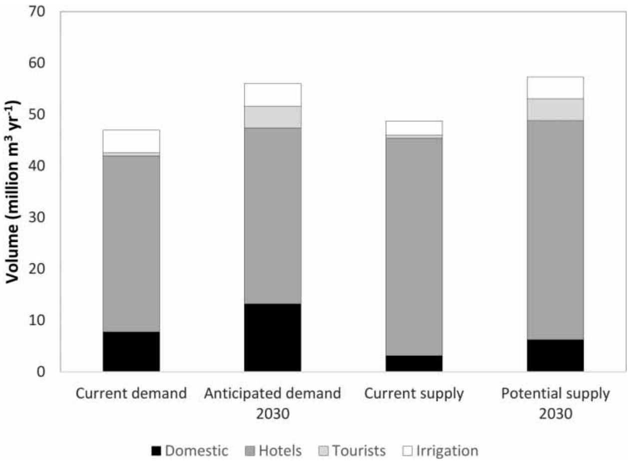

Figure 3 | Estimated future supply and demand in Sharm El-Sheikh.

The potential contribution of alternative water supply systems

This section estimates the *potential* contribution of various alternative water supply solutions to each case study under current conditions, and under estimated conditions in 2030. In terms of implementation, the likely contribution of such systems will be lower than the estimated potential, as will be discussed in the next section.

In Lilongwe, RWH, stormwater harvesting and implementing wastewater treatment and reuse were considered as feasible alternative supply sources. Under present conditions, for RWH the potential supply through the year is highly variable, concomitant with the local rainfall characteristics. Through the summer months there is almost no contribution from RWH due to low precipitation totals (Figure 4), while in the wet season (November–March) there is a considerable contribution. Over the zones studied, the total potential annual RWH supply is estimated at 800,000 m^3, with Zone 29 receiving the largest share and Kauma the lowest. For SWH, the monthly pattern is similar to that of RWH (Figure 4), with very low potential during summer months, and much higher potential in the wet months. The potential annual SWH supply from the four zones is *c*. 10.8 million m^3, with Kauma showing the largest potential due to large open areas. With respect to treated wastewater, which would be exclusively used for non-potable purposes (Jussah 2017), the volume potential depends on the assessment method. When based on actual supply from the water board and accounting for water system efficiency, present annual potential is *c*. 1.8 million m^3 based on wastewater collection fractions in each city zone and assuming optimal treatment plant efficiency. However, if the potential is based on fulfilled demand, then the annual potential could be as high as 2.9 million m^3. Given the current situation, it is unlikely that the increase in demand will be met by supply in the short- to medium-term future.

Under future conditions, this study accounted for rainfall changes (for RWH and SWH) and water supply and demand changes (for wastewater reuse). For RWH, the median (50th percentile from CMIP5 model results) results suggests an annual reduction under all four RCPs ranging from 7,000 $m^3\,yr^{-1}$ relative to present conditions under RCP2.6 to 47,000 $m^3\,yr^{-1}$ under RCP8.5 (Figures 4 and 5(a)). However, there is considerable variability when the ensemble-low (10th percentile) and -high (90th percentile) projections are considered. Under ensemble-low projections, total RWH *reductions* range from 161,600 $m^3\,yr^{-1}$ under RCP6.0 to 173,000 m^3 under RCP8.5, while under ensemble-high projections, RWH *increases* are projected relative to present conditions ranging from 92,800 $m^3\,yr^{-1}$ under RCP6.0 to 115,000 $m^3\,yr^{-1}$ under RCP2.6 (Figures 4 and 5(a)). For SWH, under ensemble-median projections, the contribution to supply may *increase* in the range *c*. 400,000 m^3 (RCP2.6) to 940,000 m^3 (RCP8.5). However, there is considerable uncertainty around median values (Figures 4 and 5(b)), with decreases of up to 2.1 million $m^3\,yr^{-1}$ or increases up to 750,000 $m^3\,yr^{-1}$ in SWH potential projected under RCP8.5 ensemble-low (10th percentile) and RCP2.6 ensemble-high (90th percentile), respectively. For wastewater treatment and reuse, potential volume contributions were estimated based on water supply and demand projections. Based on anticipated supply volumes, potential contribution in 2030 could be *c*. 2 million m^3 while if based on anticipated demand increases, and assuming the demand would be met, it could be as high as 6.3 million m^3 due to large expected demand, and therefore wastewater availability increases (Figure 2(a)).

In Sharm, only RWH and SWH were assessed. Under present conditions, RWH is estimated to contribute up to 57,000 $m^3\,yr^{-1}$, with almost no contribution through the extremely dry summer months (Figure 4). Only January and February show any significant contribution. For SWH, this water is mainly contributed from infrequent but intense, short duration flash floods, mainly in January and February (Figure 4). Of the total basin considered as contributing flood hazard to Sharm (Wadi El-Aat, Um Awadi and Wadi Kid; total area = 2,945 km^2), about 50% contributes to flash flood hazard generation (Alnedawy *et al.* 2015). Therefore, 50% of the total basin area was considered as contributing for SWH potential. The present-day potential contribution from SWH is estimated at *c*. 32,000,000 $m^3\,yr^{-1}$.

Under future conditions accounting for climate change impacts on rainfall totals, the potential annual changes to the baseline RWH considering ensemble-median projections range from a slight increase of 740 $m^3\,yr^{-1}$ (RCP4.0)

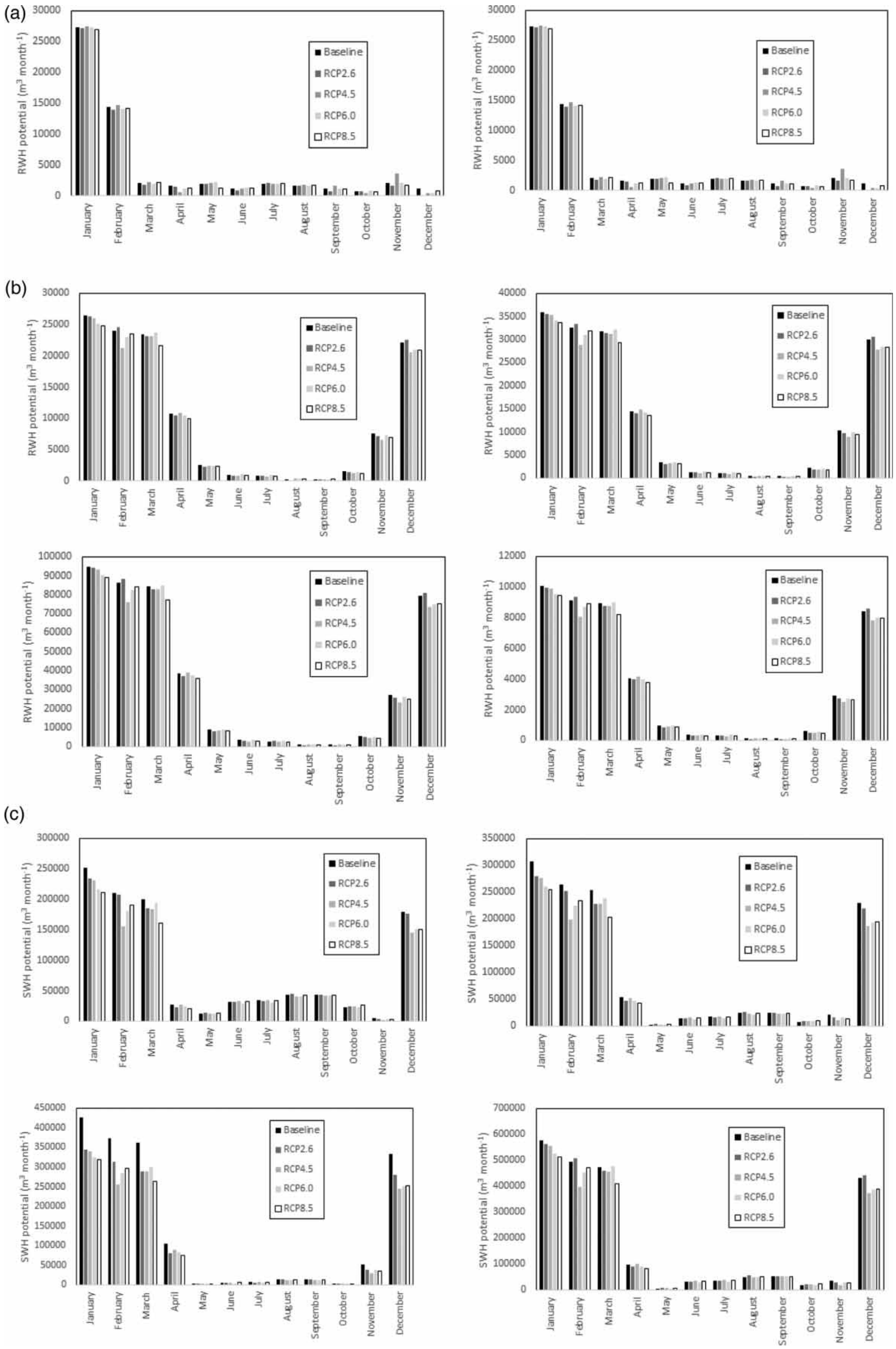

Figure 4 | Monthly potential for (a) RHW (left) and SWH (right) in Sharm for the baseline and each RCP (median RCP values shown); (b) RWH for Area 12 (top left), Area 18 (top right), Area 29 (bottom left) and Kauma (bottom right) for the baseline and the RCPs (median values shown); and c) SWH for Area 12 (top left), Area 18 (top right), Area 29 (bottom left) and Kauma (bottom right) for the baseline and the RCPs (median values shown).

to a decrease of 3,100 $m^3 yr^{-1}$ (RCP2.6; Figures 4 and 5(c)). When considering the ensemble-low and high projections, there is considerable variability, ranging from a potential *increase* of 31,500 $m^3 yr^{-1}$ (RCP2.6, ensemble 90th percentile) to a *decrease* of 22,800 $m^3 yr^{-1}$ (RCP8.5, ensemble 10th percentile). For SWH, under ensemble-median projections, the potential contribution is estimated to *decrease* between 4.7 million $m^3 yr^{-1}$ (RCP4.5) and 6.5 million $m^3 yr^{-1}$ (RCP8.5), with variability ranging from an increase up to 4.8 million $m^3 yr^{-1}$ (RCP4.5, 90th percentile) to a decrease of up to 8.5 million $m^3 yr^{-1}$ (RCP2.6, 10th percentile; Figure 5(d)) relative to present conditions.

DISCUSSION

Lilongwe, Malawi

The supply of water from LWB to the city zones shows considerable variation, although there is supply deficit in all the zones studied. High volumes supplied to the industrial zone and higher-income zones suggest a priority of supply for these zones. Generally, there is lower per-capita water demand in low income zones than in higher income zones, agreeing with previous findings (Makwiza & Jacobs 2016). Analysis of historical data shows no substantial increase in supply between 2008 and 2015. This is due to a lack of a reliable water source combined with high NRW within the network due to ageing infrastructure and a lack of maintenance.

It is projected that the water board supply system in 2030 will still be below projected water demand in the study zones, meaning that some residents will continue to suffer water shortages. Strategies on water demand management, such as NRW reduction, installation of efficient technologies and supplementing non-potable water uses with water from alternative sources (based on surveys on consumer preferences; Jussah 2017), especially for residential zones, need to be properly developed, managed and implemented to meet water demand increases. Agudelo-Vera

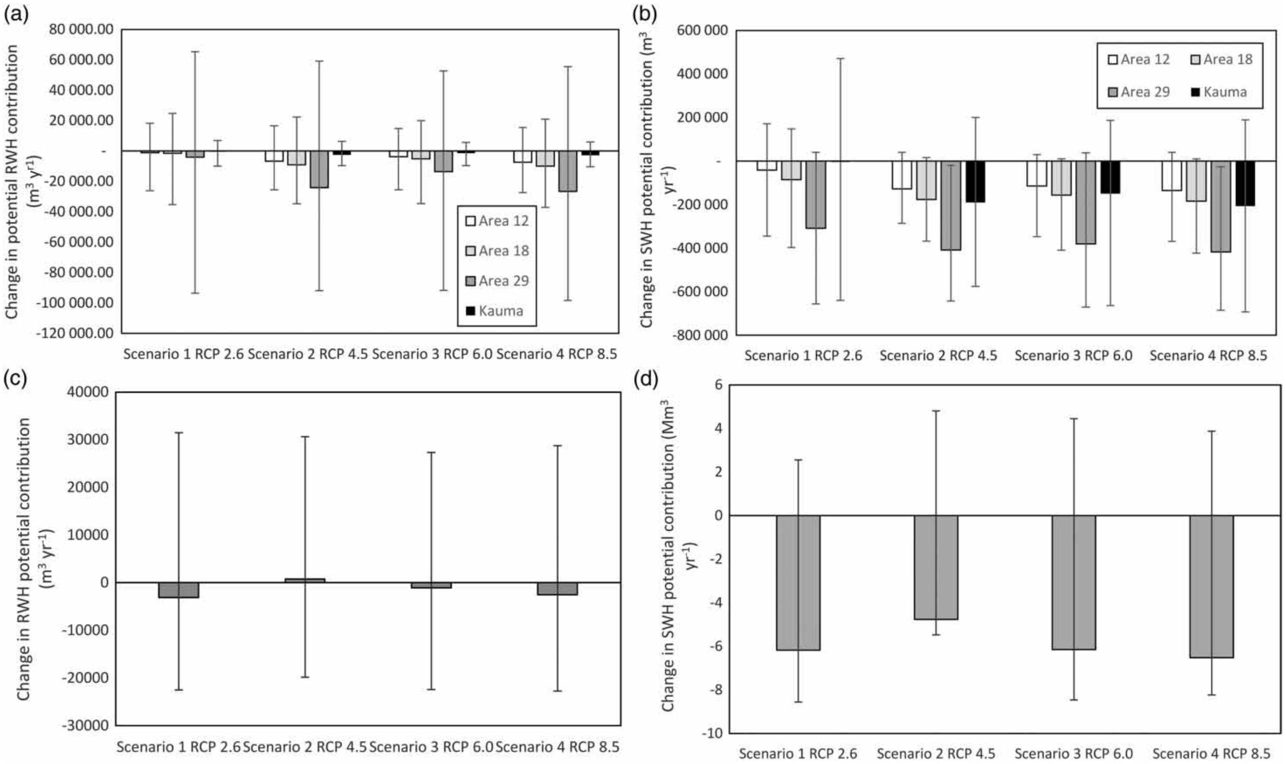

Figure 5 | Change by 2030 in potential RWH and SWH in the four Lilongwe study zones (a and b) and Sharm (c and d) under the four RCP scenarios. Boxes indicate projections based on CMIP5 model ensemble medians. Lines extend to CMIP5 10th percentiles (lower line) and 90th percentiles (upper line).

et al. (2013) recommend demand management measures at household level as one way of reducing residential water demand. Data on the growing population, the lack of water supply infrastructures due to financial challenges, and the challenges on reliable water supply sources to provide the required water supply volumes agree with previous findings on water supply challenges for developing countries generally (van der Bruggen *et al.* 2010).

On the contribution of alternative water supplies, there is high volume *potential* for the collection, treatment and reuse of wastewater in the industrial area (Zone 29) because of the high demand which is met by supply from the water board. The high potential for wastewater generation in high-income zones gives room for wastewater reuse for purposes such as municipal irrigation and industrial process use, which was seen as an acceptable use for this water source. Since wastewater supply is available throughout the year, this alternative supply is more reliable than RWH, and could contribute especially through the dry summer months (cf. Figure 4). The high potential for RWH in Zones 18 and 29 is due to the large roof size. Collected rainwater could be utilised as another alterative water source; however, strong seasonal variation (Figure 4) must be accounted for. One major implication of this variation is the need to ensure adequate storage for collected rainfall so that rainwater is still available during the dry summer months. Providing suitable storage volume could prove a barrier to implementation. For SWH, the situation is similar to that of RWH, with most contribution coming during the wetter months (Figure 4). Regarding implementation, there are currently wetland areas in Zone 18 which could be exploited as storage for collected stormwater during the wet period. The availability of cropland in each city zone also provides the possibility for local-scale stormwater storage, and allows the practising of irrigated urban agriculture since the close proximity of the water resource and the water use is an opportunity for the establishment of RWH and SWH structures (Mankad & Tapsuwan 2011). From local knowledge of the region, it appears that in Lilongwe, wider-scale implementation of SWH storage solutions might be more feasible than those for RWH. It could be envisaged that diverse alternative supply typologies are implemented according to city-zone level characteristics with some zones better suited for wastewater reuse (Zone 29), while others may be more suited to RWH (such as the lower density Zone 18). A broad suite of systems could greatly diversify water supply options in Lilongwe. Analysis of the situation in 2030 shows reduction in the volume potential from both RWH and SWH (Figures 4 and 5), but with considerable uncertainty with respect to the direction and magnitude of rainfall, making planning and financing raising somewhat challenging.

In household surveys, it was shown that residents in Kauma exhibit low willingness to adopt alternative water supply systems (Jussah 2017), which is possibly due to the low income of this zone which affects the residents' ability to pay for the technology, which is a factor affecting the adoption of new technology (J-PAL 2012). In addition, the type of shelter or houses for the residents in Kauma leaves little incentive or opportunity to install structures for the harvesting of rainwater. The potential of wastewater reuse is hampered by public perception, except in the industrial area where the water use would be for machine washing, and therefore not come into contact with people or food. SWH is generally accepted as a method for augmenting agricultural water demand, and in this regard, would face little resistance.

Sharm El-Sheikh, Egypt

Analysis of the existing situation shows that there are two fragmented systems of water supply and demand in Sharm. The tourism sector is achieving water surplus due to: i) recent tourism decline; and ii) the considerable development of the desalination industry to fulfil a demand that is not being met, which is largely due to long-term contract obligations. The current surplus can fulfil tourist water at full occupancy rates (Orabi 2017), however occupancy is considerably lower than the maximum at present. The tourism industry achieves self-sufficiency of water supply and supply autonomy through an ability to pay the higher rates for this service. Conversely, the public water supply is suffering from water shortages and there is a significant gap between supply and demand for local residents. Possible reasons for this gap are: i) population is higher than official figures due to informal migrant workers; ii) higher water consumption per-capita than official figures suggest; iii) an inefficient network with high NRW; and iv) a general inability to pay for desalinated water rates. NSCWW considers a population of 35,000 with a per-capita demand of 250 L cap^{-1} day^{-1}. However, there is no accurate census data for population in Sharm, and non-registered people are not considered as water consumers. However, the majority of Sharm's population are temporary migrant workers. According to a survey by UNISDR, the population of Sharm in 2009 was estimated at around 85,000 (UNISDR 2011). The 250 L cap^{-1} day^{-1} may be an underestimate for reasons including: (i) large losses in the public water network; (ii) high water consumption in this hyper-arid region; (iii) lack of awareness on water conservation of water consumers who are mostly temporary workers; (iv) increasing life standards in the city among permanent residents; and (v) a very low price of subsidised public water (Lamei *et al.* 2009a, 2009b, 2009c) which discourages water saving habits.

Water is not equitably distributed in Sharm, due to a complex, bi-partite system. The water supply–demand gap in the public network is anticipated to increase by 2030, whereas the existing surplus of hotels can easily accommodate expected increases in occupancy. Co-operation between concerned authorities from public and private water sectors is required to manage the situation. For example, NSCWW could consider negotiating to buy surplus water from the hotel industry, and supplying this at a subsidised rate to the public. Analysis in this paper suggests that the current tourist surplus could cover a large part of the public supply–demand gap. Managing water demand should also be considered to decrease the current gap. Demand management interventions must be taken to tackle the technical and economic problems regarding water supply of local inhabitants in Sharm. Possible options include: adjusting the subsidy system to control high consumption; installing metering systems to better quantify actual per-capita consumption rates and patterns; installing leakage detection systems; upgrading the public water network to reduce NRW; encouraging the installation of low water use appliances, possibly through rebates/tax incentives; and using municipal plantations that suit with the natural desert landscape to reduce irrigation water use (Lamei *et al.* 2009a, 2009b, 2009c).

The potential contribution of RWH is negligible and is not reliable (Figure 4). SWH has higher potential contribution, although climate change projections suggest a reduction in the SWH contribution by 2030. SWH is highly seasonal (Figure 4), and as in Lilongwe, storing and distributing large volumes of water that are delivered in a very concentrated time span could prove challenging. Despite this, significant amounts of water could be added to the existing water supply system after suitable treatment. Additional water would largely be used for irrigation and other non-potable applications, but the infrastructure must be developed for this purpose. The feasibility of SWH will largely be determined by the costs of implementing SWH infrastructure (namely storage and distribution), public perceptions regarding the use of stormwater and the concomitant demand for the water, and the benefits that could be gained from the water. Public–private partnerships (PPPs) are successful in the desalination industry in Egypt generally and in Sharm particularly. They have helped hotels to produce their own water and achieve self-sufficiency. The government could similarly motivate private water companies to invest in SWH infrastructure in Sharm for public distribution. However, as with many PPP schemes, caution should be taken to prevent the private water companies dominating the water sector.

Synthesis

The results from the two contrasting case studies (Table 1) present issues in meeting the public water demand for a number of reasons. Growing populations and unreliable conventional water sources with extreme seasonal variation (Figure 4) are among the major reasons, but poor supply network efficiency (leading to high consumption rates), low coverage rates and a bi-partite supply system (in Sharm El-Sheikh) are also important considerations, as is cheap, often highly subsidised water. There is a clear need for demand-side measures in both cases. However, alternative supply sources can play an important role in bridging the supply–demand gap, especially if targeted for non-potable uses which can consume considerable water volumes in urban areas. The city of Sharm is well placed for desalination, which is already being used, mainly in the private hotel sector, and could be expanded to the public sector if the cost can be reduced (perhaps through government subsidies to make it affordable to local residents), while in

Table 1 | Summary of the main commonalities and differences between the case studies

Lilongwe	**Sharm El-Sheikh**
Humid climate, ample rainfall	Hyper-arid
Overexploited traditional sources	No viable traditional sources locally
Little use of AWSs at present	Desalination is the main freshwater source
High potential for RWH, SWH and wastewater reuse depending on city zone	SWH offers high potential, but with considerable capital investment. Desalination will continue to dominate
Address closing the supply-demand gap	Address inequities in water provision between private and public users
High NRW and system inefficiencies must be addressed	
Climate change impacts may reduce potential yield of AWSs	
Public preferences and perceptions will shape the typology, location and scale of AWSs	
Financing, governance and capacity challenges	

Commonalities are shown across both columns in the table (in grey shading).

Lilongwe, rain- and stormwater could contribute additional water for non-potable uses. Treated wastewater in Lilongwe has the potential to serve industrial processing demand. If applied with well-targeted and well-managed demand management, both cities could achieve supply–demand parity and a more equitable water supply system.

There are challenges to be overcome. One major challenge is uptake and implementation of alterative water technologies and infrastructure. Finding and implementing suitable storage solutions to cope with the highly concentrated water supply through the year (Figure 4) is a major obstacle, as is the requisite infrastructure network for distribution and treatment. Local features such as wetlands can be exploited for storage purposes, reducing costs. There is also a need to evaluate the preferences regarding the use of alternative water in order to ensure that appropriate systems are designed and implemented. High-resolution, local-level questionnaires could help elucidate some of these uncertainties. Initial results give insight into these issues (Jussah 2017), however a more thorough investigation at the city-scale would be necessary for wider consideration of alternative systems. This study suggests that rainwater would face few obstacles for many uses so long as storage could be found. Stormwater is favoured for agricultural and other irrigation purposes, while treated wastewater is favoured for industrial use. Implemented systems may differ in terms of typologies, location, size and end-use according to the expected demand for the water and the expected use of this water. This diversity in typology and end-use not only could help boost water supply, but also contributes to increased resilience in the water supply networks, and reduces the pressure on traditional water supply sources. Incorrect implementation would lead to inefficient use of financial resources which may have been better spent on measures such as network improvement. For example, in Lilongwe it is suggested that wastewater would be readily taken up in industrial zones, but not in residential zones. The costs and benefits of alternative water supplies against network improvement would need to be assessed.

Related is the issue of public perception and acceptability of alternative water. While desalination and RWH are generally well adopted, the use of stormwater, and especially of treated wastewater, can encounter perception issues. Education and awareness raising regarding the quality of the produced water, as well as advice on best-practice regarding the use of alternative water may help alleviate some concerns. Questionnaires and surveys regarding potential uses of alternative water can assist in planning and designing systems to ensure that supply (quantity, quality, typology) fits with the demand. For some water (e.g., treated wastewater), formal use restrictions can temper safety concerns.

There are financial and political constraints. For larger schemes, financing and political willingness for such schemes may be lacking, while for smaller systems such as on-site RWH, residents either may not have the funding and/or space to implement these systems or may not see the need for implementation. In Sharm, a PPP setup for the desalination plants offers a potential avenue for future exploration. With support from public bodies and financing from private institutes, arrangements could be made that suit both parties, that supply water and that help bridge supply–demand gaps. Such arrangements are more likely to be feasible for larger investments such as SWH (in Sharm and Lilongwe), changing the desalination industry model to ensure more equitably distributed water (Sharm) and implementation of wastewater collection, treatment and reuse (Lilongwe). Some of these constraints and challenges are related to ensuring appropriate levels of water treatment to suit the end-use (e.g., cost and energy implications of treatment, perception issues surrounding the quality of the water produced). It is assumed throughout this work that treatment suited to the end-use of the water would be put in place; however, the water quality aspect was not considered explicitly during this study, which was focused on assessment of alternative sources as a potential way to address water supply–demand gaps.

Other measures may be more suitable than alternative water supply system development and/or enhancement. Although this study shows that alternative systems have potential, and that diversification of supply sources can enhance resilience to uncertainty, other measures may be equally beneficial. Investment in network upgrades to reduce NRW is one measure that does not require new infrastructure development. Orabi (2017) showed that halving the current NRW values in Sharm could contribute to a significant reduction in the supply–demand gap currently observed in the public network. Likewise, demand-side measures such as rebates or discounts on efficient water-using appliances could also lead to demand reductions through the network. Ultimately, it is likely that a combination of supply enhancement and diversification and demand-management may be the best approach to addressing water security issues in the study cities. The issues highlighted here are applicable to many other cities in similar settings, with locally specific issues driving alternative water supply development opportunities and challenges.

Through the two case studies in this paper, focusing on cities in developing countries, a few key messages are highlighted:

1) Account for the local climatic context, especially seasonal variation when assessing the viability of various AWSs, particularly in regard to storage of collected water. For example, in Sharm El-Sheikh there is little benefit of RWH, and while there is more potential for SWH, storage and distribution of collected water is an issue.
2) Carry out high-resolution residential surveys in order to gauge the demand for alternative water and assess the potential uptake of these systems, and the probable end-use of this water in order to guide decisions on system typologies. Incorrect or insufficient information could lead to under-used systems being implemented. In Lilongwe, for example, SWH would primarily be used for agricultural and other irrigation, while treated wastewater was only deemed suitable for industrial processing.
3) Incorporate considerations surrounding financing, governance and capacity to plan, build, operate and maintain larger-scale systems. There remain many technical, financial and institutional challenges regarding the implementation and uptake of alternative systems, especially larger systems.
4) Account for potential changes to anticipated yields as a result of climate change.
5) Supply augmentation must be combined with demand management strategies in order to close the supply-demand gap. No single strategy will solve all the issues being faced.
6) Water quality, and treatment appropriate for the end-use must be put in place to overcome perception issues, but this comes with a financial and energy cost.

It is shown that AWSs do have potential in both case studies, but that the typology, end-use and challenges being faced are very different. If implemented well, AWSs have the potential to reduce pressure on traditional water sources, close the supply–demand gap and enhance water supply system resilience by increase the diversity of supply options.

CONCLUSIONS

This study focusing on the potential of alternative water supply solutions in Lilongwe and Sharm El-Sheikh has highlighted important similarities and differences between these contrasting cases, and shows some of the opportunities and challenges for the implementation of such systems. A relatively simple, fast and resource/data-light methodology is adopted to give first-order estimates of the potential of alternative water supply systems. Such an approach may prove beneficial, especially in developing nations/cities who may lack the up-front resources for more sophisticated investigations. Lack of local data to support sophisticated modelling approaches is often raised as a potential barrier to water security assessments and planning in cities with limited institutional capacities; this study places particular emphasis on remediating this common obstacle by developing high-level assessments based on datasets and online tools easily available worldwide. While recognising the limitations and uncertainty attached to the presented results, this is suggested as a first step for developing cities to become acquainted with their potential resources available within their city boundaries, while capacity to refine estimates and develop assessments to a greater level of detail can be sought and developed as needed at the next stage of the process.

In Lilongwe, it was shown that collection, treatment and reuse of wastewater and stormwater runoff could add considerable volumes for non-potable use, although the exact use of the water would be very different based on user preferences and city zone type. For example, wastewater is only acceptable for industrial processes, while rainwater is more generally acceptable. Apart from diversifying and boosting water supply, Lilongwe should also address high NRW losses in the system to enhance system performance and close the supply–demand gap. Although there are attempts to increase water supply to the city zones, the expected change in water supply does not match expected demand increases, and inequitable distribution is expected to remain unless other measures are taken. In Sharm El-Sheikh, desalination currently supplies most of the freshwater, while treated wastewater supplies irrigation uses. Water is unequally distributed, with tourism activities consuming the major part of desalinated water supply while the local population experiences water shortages from the public network. Expanding the public desalination industry, and making it more affordable through subsidies, along with NRW reduction, could reduce the local supply–demand gap, but changes to the contractual set-up are required that would free up excess desalination water currently produced for hotels to be used in the public network at an affordable tariff. Stormwater could be harvested for non-potable uses, but would require considerable investment, and storage provision to address the fact that this water is delivered at high volume in a short space of time needs to be addressed. Issues on public perception and governance also need to be tackled to ensure infrastructure development and improved equitable water distribution.

Both locations, while very different in character, illustrate similar opportunities and challenges. Alternative water supplies could help boost and diversify supply, improving resilience to future changes. They could also prove useful for many non-potable uses, and therefore help to reduce pressure on the traditional water sources, which could be prioritised for potable use. However, any such investment must be carefully planned and managed to ensure that appropriate systems are installed in suitable locations to match the expected end-uses and that are suitable for climatic, social and institutional settings. Storage solutions to buffer considerable seasonal rainfall variations in both locations are needed, as is the infrastructure for treatment and distribution. Financing for implementation of larger systems could also be a challenge, and there are issues surrounding political willingness, and public perception of the different alternative systems considered. This will require investment plans based on investment pathways that reduce water risks at least cost over time (i.e., are sustainable) and ensure synergies and complementarities with investments in other sectors (i.e., economies of scale, win-win solutions). This requires evidence-based (long-term) investment scenarios towards sustainable development. Institutional and governance processes are required to ensure equitable supplies throughout the cities. Both cities should also consider demand management, especially NRW reduction, as an initial step towards ‘quick win’ results.

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