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Modelling scenarios for water supply and sanitation technologies in Jordan

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The influx of refugees, population growth and current agricultural practices have led to an increase in water demand in Jordan, placing pressure on existing water provision. Climate change further exacerbates declining water availability. Against this backdrop, the techno-economic feasibility of four water supply and sanitation alternatives for small and medium scale cities in Jordan were explored, using local unit costs and Al-Mafraq as a case study. City level piped network combined with household rooftop rainwater harvesting and surface runoff collection into local ponds and piped networks with treatment using the nature-based solution of root-zone for sanitation were demonstrated to provide the highest benefits in terms of cost, convenience and water conservation. Our work highlights the need to invest in long-term urban infrastructure networks to promote sustainable future growth of cities. This is vital to address severe water scarcity challenges that ultimately impact those at the urban fringes most.

Jordan, a water-scarce country with highly variable climate, faces many challenges regarding water provision[1]. Annual rainfall averages 250 mm, ranging from 30 to 570 mm depending on the region[2] (see Fig. 1[3]), falling largely during winter from October to April. Annual water availability–mainly from surface (59%) and groundwater (27%)[4]—is between 100 and 200 m^3 per capita, out of which only 42% is available for domestic consumption[2,4,5]. Jordan is home to around 655,000 registered Syrian refugees, living both in urban areas and camps[6,7]. As of late 2023, Jordan hosted around 720,000 refugees, with 650,000 from Syria[8], representing around 6% of the total population in Jordan considering the 2015 census estimated population of 11.3 million people in 2022[9]. The influx of refugees has brought higher water demands, further aggravating the water-related challenges[2,5]. Water consumption per capita in Jordan is around 90 L per day[10], and according to the Ministry of Water and Irrigation (MWI), 96% of the population in Jordan, including refugees renting apartments, are connected to municipal water networks in urban areas and 88% in rural areas[11]. Similarly, a UNICEF study[4] reported that 74% of the households in Jordan cities are connected to municipal water networks, with the remaining 26% using water vendors and bottled water, supplemented in rare cases by rooftop rain harvesting.

Climate change has had an impact on increasing temperature, variations in weather and rainfall patterns, including flash floods and extreme weather events, posing challenges for the resilience of water and sanitation services. Water resources have also been overexploited by the agricultural sector[2,5]. The rate of groundwater annual abstraction exceeds the renewable average of recharge[12], with long term observations of groundwater deposits and aquifers suggesting a dramatic decrease in water levels, with declines of more than 10 m in some instances. In addition, the average non-revenue water (NRW) rate is around 60–65%, where up to 20–50% of water is lost due to leakages[5]. Utility companies increase water pressure to meet demand, further damaging the system[5]. In view of the scarcity and challenges utilities face, the municipal water supply is usually rationed and intermittent[13].

Around 63% of Jordan's urban population is covered by sewerage networks and 30% use alternative house level sanitation treatment methods such as septic tanks or cesspits[14]. The remaining 5% do not have in-house sanitation facilities and depend on community facilities or public latrines. While efforts have been made towards sanitation planning at different scales incorporating alternative sanitation and reuse approaches, there are still issues of coverage, domestic water management, sustainable solutions and funding[15].

Mafraq governorate is located near the border with Syria. As a result, it is the second largest area hosting off-camp refugee population, with thousands of refugees having settled in the city of Mafraq[16,17]. Since then, the city has been a hotspot for local and international agencies and donors working on water scarcity. The work presented in this article derives from a larger research project that sought to re-think humanitarian aid for refugees as investments in urban water and sanitation, as response models based on camp systems are not viable in urban settings[18]. In this article, evidence from 165 household surveys was used to evaluate the current water and sanitation

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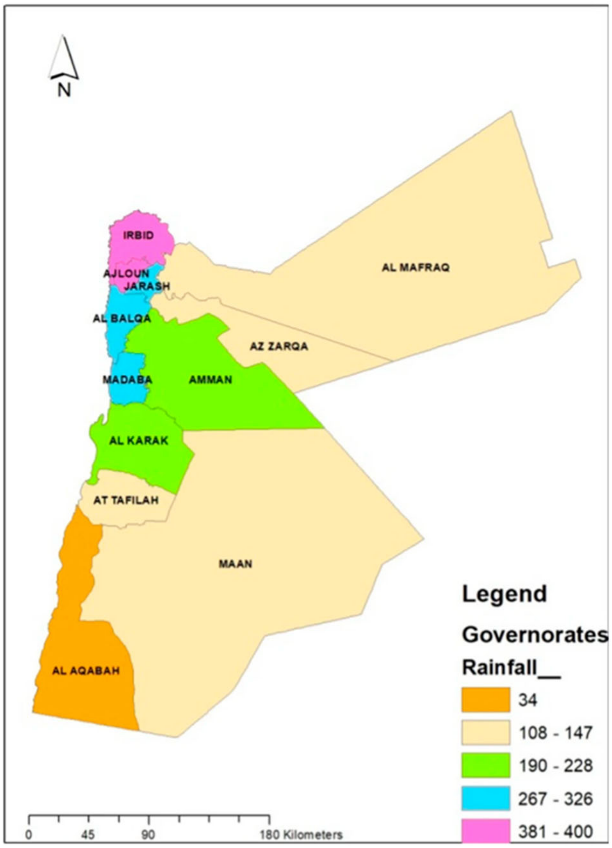

Fig. 1 | 'Average annual rainfall distribution in the governorates of Jordan' (mm/yr), by Al-Qawasmi[3], licensed under CC BY 4.0.

connectivity and practices in Al-Mafraq city and secondary data was used as a database to represent a typical Jordanian city to explore the techno-economic feasibility of four different water supply and sanitation strategies for small and medium scale cities of Jordan to meet current deficiencies.

Results

Current water and sanitation situation in Al-Mafraq

The household survey encompassed mainly Syrian refugees, constituting two-thirds of the participants. Almost two thirds of participants (57.6%) lived in a bungalow and there was an average of 2 apartments per building. Almost all premises had a flat roof (92%), making rainwater harvesting technically viable.

The main identified issues included that despite high connectivity to the municipal water network (90.3%), 53.7% of participants could not meet their needs with municipal water. This means that they obtain additional water (65.1%), sometimes from several sources, to cover their needs at a high cost–such as bottled water (61.9%) and/or through trucking (79.4%; mostly used in emergencies, 72.7%). Additionally, most participants rely in water storage in either roof tanks, ground tanks or a combination of both due to intermittent supply.

53.7% of participants get water from the municipal network once a week, 44.3% get water twice a week and the remaining get water once every 2 weeks. A third of participants (34.2%) get 4 to 8 h of water daily, 23.5% get less than 4 h per day and 18.8% get 8 to 12 h of water daily. The remaining 23.5% get over 12 h of water daily. The average spending on municipal water services is of 12.11 JOD/USD$ 17.08 per month, with the highest spending being 50 JOD/USD$ 70.52 (14.3% of the monthly income if earning 350 JOD/USD$ 493.65 a month).

Participants purchase a median of 3 m^3 of water (with a minimum of 1 m^3 and a maximum of 20 m^3), costing a median of 12 JOD/USD$ 16.92 (min = 4 JOD/USD$ 5.64; max = 80 JOD/USD$ 112.83). Participants pay an average of 2.6 JOD for 20 L bottles from private vendors and buy an average of 4.3 bottles.

The majority (69.1%) of respondents do not think the water is of drinking quality. As a result, 44.2% treat water at home, especially municipal network water (80.8%) and, to a lesser degree, trucked water (43.8%). The most common treatment process is commercial water filter (86.3%). A slight majority of households (58.8%) do not recycle water; those that do (41.2%) recycle it to clean the home (47.1%), horticulture (57.4%) and toilet flushing (23.5%).

In terms of water storage, roof tanks were prevalent (92%), although only a slight majority (58.2%) only uses roof tanks for storage. The second most common storage strategy is ground tanks (30.1%), although these are usually combined with roof tanks (20%). Water tanks cost a median of 12 JOD/USD$ 16.92 (min = 4 JOD/USD$ 5.64; max = 80 JOD/USD$ 112.83) and participants purchase a median of 3 m^3 of water. However, 82.6% reported municipal water not reaching their tank, which has led to 90.2% of households to purchase a water pump (median power of 0.5 Horse Power) that costs an average of 37.5 JOD/USD$ 52.89. Rainwater storage garnered little interest, with 88.5% expressing disinterest, citing cost (53.4%) as the primary barrier.

Almost all households have a usable private toilet (98.8%), with an average of 1.5 toilets, predominantly pit latrines (56.4%) or a combination with ventilated improved pit latrines (26.4%). 52.8% are connected to the sewer and 46.6% to septic tanks/cesspits (some are connected to both, 0.6%). Most households (76.6%) paid for septic tank emptying, averaging 7 times in 5 years. There was an even split between households that pay for sanitation services when they pay water bills and ones that do not. Most participants did not report the amount paid for sanitation services (quantity unquoted); of those who provided an amount, the average spending was 3.35 JOD/USD$ 4.72.

Discussion

Our analysis showed that at household level, rooftop rainwater harvesting can barely meet the daily water needs and is not very effective in the dry summer months. This is reflected by the survey respondents showing weak interest in rainwater storage. Although rooftop rainwater harvesting can potentially meet only 6% of the assumed daily water need (i.e. 6 L out of 100 L) it was included in the options to underscore the desperate scarcity of water in Jordan and the need to conserve it, especially when the additional cost in the long run is significantly less than making up the shortfall through alternative means such as vendor supply. Despite the average rainfall in the country being so low and the existing constraints to water harvesting, the total water captured each year by rooftop harvesting comes to 12 m^3 per household, which otherwise would cost 30 JOD/USD$ 42.31 if supplied by tankers. This annual cost when capitalised at the bank interest rate of 4.5% comes to around 666 JOD/USD$ 939.35, which is far greater than the capital cost of 236 JOD/USD$ 332.86 for water harvesting tank and pipes. The decision as to invest in rooftop harvesting or incur greater expenses over a long term, however, lies within the households. The aggregate roof terrace area is such a small fraction of the overall city area that the reduction of surface flows downstream for other uses is relatively low. Therefore, compared to rooftop rain harvesting, it would be far useful if storm drainage was designed to channel the larger city level flows to the surrounding water reservoirs.

Rainwater harvesting and house underground tank supplemented by private vendors (Water Option 1) is prevalent in areas of Al-Mafraq where householders do not have access to piped water network supply[19]. The high initial capital investment of underground tanks (6060 JOD/USD$ 8547.25) is coupled with high recurring costs of vendor supply (10,102 JOD/USD$ 14,248.23), making this the most expensive solution (16,162 JOD/USD$ 22,795.49). This scenario shows the high financial burden placed on households in absence of infrastructure systems[20]. Further, the quality of water from vendor supply is often poor, needing additional treatment before drinking, adding further to energy costs and consumption[19]. Both in terms of cost and long-term sustainability, this is not an ideal solution and not advised except in emergencies.

Local piped networks supplying part of the daily need and vendor supply supplemented by rainwater harvesting through household underground tank (Water Option 2) is a hybrid solution prevalent in Al-Mafraq city and many other cities of Jordan[19]. Compared to Option 1, the initial capital cost of delivering this option from scratch increases (6503 JOD/USD$ 9172.07) due to delivering piped networks but the recurring costs of vendor supply reduce to almost half in comparison to Option 1 (5488 JOD/USD$ 7740.48). Nevertheless, the total cost of this option remains quite high (11,991 JOD/USD$ 16,912.55) and not sustainable in the long term, in part due to the high costs of large underground tanks.

Fully piped city network supplemented by rainwater harvesting and house underground tank (Water Option 3) has the highest initial capital costs (6662 JOD/USD$ 9396.33). However, the recurring costs of the system are much less (693 JOD/USD$ 977.43), reducing the total cost significantly (7355 JOD/USD$ 10,373.77). In addition, the system has the potential to reduce the water quality concerns of the earlier options. The high capital costs are in part due to the costs of the underground tank and can be reduced for settings where tank structures already exist.

Option 4 is similar to Option 3 of rainwater harvesting supplemented fully piped city network except that house underground tanks are replaced by small plastic tanks for rainwater harvesting at household level and large surface runoff water collection ponds spread across the city to meet the deficiencies in the dry months. Because of the economy of scale of centralised collection ponds and lower costs of plastic tanks, the initial capital costs reduce drastically (1132 JOD/USD$ 1196.61) and has low operation costs. In addition, as with Option 3, the system does not have water quality concerns of the vendor supply option. Surface runoff quantity is substantially higher than rooftop harvesting and increases water availability significantly if collected in ponds. This water has the potential to be reused for agriculture, recharging the water table or, if treated, for drinking.

The costs of water networks (Water Options 3 and 4) are assumed anew, but as parts of the city already have some water networks, the actual additional cost would be even less than estimated. All piped water options are priced to supply water at appropriate pressure to avoid pumping at house level, as the accumulated pumping cost at individual houses is far greater than the costs of city level elevated water tanks fed by centralised pumping from the water sources.

NRW is one of the most pressing problems of municipal water systems in Jordan, with Al-Mafraq facing up to 79% of water lost to NRW[4]. Despite the use of smart water metering systems for individual and bulk metering to identify NRW zones and locating unaccounted losses from leakage and pilferage, approximately half of Jordan's domestic water supply is still lost through leaks, aging infrastructure, theft, inaccurate metering or data processing errors[21]. Results from the survey reflected participants' experiences of low water pressure, potentially explaining the discrepancies between high connectivity but poor supply.

Water consumption in Jordan is often controlled by rationing water with intermittent supply[13,22]. This is reflected in the high percentage of participants with water storage tanks. Restrictions cannot be a long-term solution to water problems, as the longer or higher restrictions are, the higher the impacts on welfare loss, damage and interference with market mechanisms controlling demand and supply[23]. Other issues include water competition by installing suction pumps on the network leading to lower pressure at the network's fringes and theft. Also, the peak flows in the pipes increase with intermittent supply. The water hammering effect every time the mains water is switched on and off can damage pipes and joints, increasing system costs[24]. Instead of rationing water, water metres already in place can be used to recover the city sewerage costs with exponentially increasing tariff. Water options 3 and 4 move towards addressing the challenges of NRW by developing new piped networks which promote 24-h water supply to reduce water hoarding. In terms of additional water, supply from vendors (trucking and bottled water) is not a long term and viable solution to cover water needs in terms of sustainability, cost and needs. Vendor supply is costly and should be limited to some non-domestic uses and emergency shortfalls.

The sanitation landscape was further limited, with only slightly over half of participants reporting being connected to the sewer system and the remaining participants relying on septic tank/cesspit connections. Individual house level septic tanks/cesspits and soakpits, with common sludge beds sized for 5500 families each but without any public sewer networks (Sanitation Option 1), is a decentralised option in which the householders largely manage on their own resources. This is the current situation in areas without sewerage networks and, particularly, in the areas where Syrian refugees have recently settled[19]. The total cost (1166 JOD/USD$ 1644.57) is slightly lower compared to the other sanitation options, however, this is the most expensive option in terms of initial capital investments (726 JOD/USD$ 1023.98) and moderately high recurring running costs (440 JOD/USD$ 620.59). Whilst this option may serve immediate needs, it is not an ideal solution in terms of costs, future development of city infrastructure or long-term sustainability. This solution is, therefore, not advised except in emergencies.

Local level piped sewer networks leading to common septic tank and soakpits serving clusters of around 250 houses, again with common sludge beds sized for 5500 families each (Sanitation Option 2) is an intermediate scale solution which has the potential to be upgraded to a city level sewerage system with sewage treatment plants. The economy of scale by using common septic tanks and soakpits reduces the initial capital investment (688 JOD/USD$ 970.38) to less than Sanitation Option 1 despite the addition of the local sewer network. The recurring costs (480 JOD/USD$ 677.01) increase slightly in comparison to Sanitation Option 1 because of the running costs of the added local cluster level sewer networks. Nevertheless, the combined initial capital investment and the subsequent operation and maintenance costs (1168 JOD/USD$ 1647.39) of this cluster level solution still works out to a similar amount to that of Sanitation Option 1. This solution is challenging to implement as the utilities would need to consider how the ownership of asset would work for neighbourhood clusters. Nevertheless, the combined initial capital investment and the subsequent operation and maintenance costs (1168 JOD/USD$ 1647.39) of this cluster level solution is still lower than Option 1.

In both Sanitation Options 1 and 2, soakpits would not work well in areas where the water table is high or where the soil is non-absorbent clay or rock. Further, there is a risk that the absorption of semi-treated sullage from the soakpits into the surrounding soil may pollute the groundwater table over time. As groundwater is one of the sources of water supply, this may deplete a potentially critical water supply resource.

Option 3 includes city level piped sewerage networks connected to conventional activated sludge sewage treatment plant. This option has the highest total cost (2383 JOD/USD$ 3361.07) as it requires a moderate capital investment (709 JOD/USD$ 1000.00) but the running costs are very high (1674 JOD/USD$ 2361.07). Quite often mechanical treatment plants consume high amounts of energy, making them expensive to operate and maintain[25].

City level piped sewerage networks connected to a nature-based treatment using reeds (root-zone treatment; Sanitation Option 4) has the lowest total cost (1088 JOD/USD$ 1534.56). The initial capital investment (763 JOD/USD$ 1076.16) is high because of the extensive sewerage network and the addition of root-zone treatment plants. However, the recurring operational and maintenance cost (325 JOD/USD$ 458.39) reduces substantially as desludging, a major cost component, is not required in this option. Additionally, the system does not have the water pollution concerns of Sanitation Options 1 and 2 which use soakpits to leach the sullage into the ground. The costs of sewerage water network are assumed anew, but as parts of the city already have sewer lines, the actual cost of this option would be even less than estimated. Root-zone sewage treatment was selected as it is a simple and natural method not requiring cumbersome mechanical and electrical inputs. Further, the system can be designed to treat almost 80% of sewage to river discharge standards to recover and recycle water back into the water supply system, albeit with additional processing to render it potable–an advantage in a country with water scarcity.

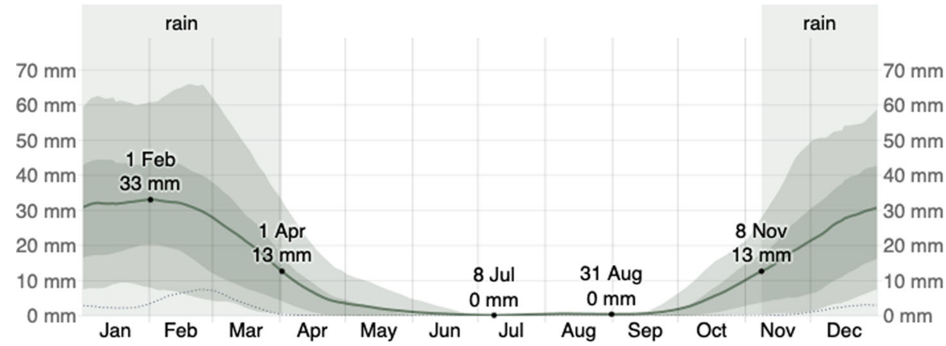

Fig. 2 | Al-Mafraq average rainfall (solid line) accumulated over the course of a sliding 31-day period, with 25th–75th and 10th–90th percentile bands. The thin dotted line is the corresponding average snowfall. Image source: © WeatherSpark.com.

There is a need to invest in longer term infrastructure to support future population growth and build resilience against climate related impacts, particularly in water-scarce regions. The increase in refugees, population growth and current agricultural practices have resulted in higher water demand in Jordan, straining the existing water supply – which will be further aggravated by climate change. The figures presented on the cost comparison across water options illustrate that individual household water storage tanks in aggregate are for more expensive than centralised storage reservoirs. Further, the figures show how significantly the capitalised O&M reduce as once transitions from vendor supply to city level water networks. On this basis, city level piped water network combined with household rooftop rainwater harvesting and surface runoff collection into local ponds (Option 4) is recommended on grounds of economy, convenience, water quality, conservation of water and sustainable future growth of the city. In terms of sanitation, based on the calculations presented, piped sewerage networks with treatment using the nature-based solution of root-zone (Option 4) is recommended on grounds of costs being substantially lower than conventional treatment, operational ease, conservation of water and development of long-term urban infrastructure networks to promote sustainable future growth of the city. This option is also more suited for a city with a high population growth rate, as it can adapt to increasing population at a fraction of the cost that would be needed to do the same by the first two sanitation options.

This study is of broader interest to similar cities in the Middle East and other arid areas, as it touches on key challenges faced in arid small town and rural areas and addresses the relative cost of alternative systems. Our work shows that from an operation and maintenance perspective, networked infrastructure is less costly in the long run and more effective for households, as well as provide the highest benefits in terms of convenience and water conservation. If this is combined with nature-based solutions at scale, such as rainwater collection ponds and root zone treatment plants, it could be rediverted to meet agricultural water needs and free-up available clean water for domestic purposes, as a supporting measure to address the severe water scarcity challenges facing cities in Jordan. For this to work, however, it is important for water quality to align with the WHO guidelines for drinking-water quality and the technical regulations of the Jordan Standards and Metrology Organization. Our modelling further shows that there is value addition in investing in water and sanitation infrastructure networks which can provide reliable water supply and wastewater collection, which has great potential to contribute to SDG 6 on access to water and sanitation for all.

Methods

Household surveys were used to evaluate the current water and sanitation connectivity and practices in Al-Mafraq city and secondary data, using Al-Mafraq city as a case study, was used as a database to explore water supply and sanitation systems alternatives across different scales and using alternative technologies to meet current deficiencies.

Case study: Al-Mafraq city

The water distribution network in Al Mafraq covers around 3256 km in length[26] and serves 98% of the population[10]. The network pumps ~29 million m^3 of water to the governorate. Given the old age of pipes and the length of the water supply maintenance is low and inspection is slow in reporting seepage and leakages[27].

As per the 2015 Census data of Jordan Department of Statistics, the urban population of Al-Mafraq Qasabah (the city centre) was 142,844 out of which about 38% constituted Non-Jordanians[28]. The gross area of Al-Mafraq city is 72 km^2[2,29]. Excluding the vacant land in the city (almost 50%) plus road and non-residential areas, the average plot area per family works out at just under 400 m^2 and the average road front width is about 20 m[29]. This population density and the average plot width measurements were used as the basis to calculate the lengths of water supply and sewerage pipelines in the cost analysis. The pipe diameters were estimated based on the population served and the target of daily water consumption per capita of 100 L[14]. These norms have been developed from a large database resulting from numerous water and sanitation projects designed by the authors at various scales in many regions.

Data from a sample survey of 200 households conducted by Al-Mefleh et al. in Al-Mafraq in 2019 was used to develop the scenario model[19]. The survey revealed that 73% of households depend on the public water network from the directorate of water in Al-Mafraq governorate but 71% reported that the amount of water pumped fails to meet their needs[19]. Furthermore, 87% reported depending heavily on groundwater wells to cover part of their water needs, much higher than the national average. An additional 6% generate some water by rooftop harvesting (during rainy season) and 24% reported buying water from groundwater wells from private tankers. As for the residents who are not connected to the water service, they depend on other water sources, such as rainwater harvesting, use of private tanks, bottled water, etc.[19].

The same survey showed that, with respect to sanitation, only 12.1% of households are connected to a sanitation system (25% of which are sewer system) and a further 87.9% use septic tanks/cesspits that add extra costs for the disposal of sewage, contrasting the national figures reported by the MWI of 68% of households having a sewer connection[11] and showing spatial variability in service coverage to the disadvantage of rural areas. The reliance on the use of septic tanks has directly affected the quality of water due to the pollution leakage from the tanks[19].

Al-Mafraq is an arid area with an estimated 150 mm to 300 mm annual rainfall which falls in two main seasons: summer (beginning mid-May until September) and winter (November until the end of April)[30,31], see Fig. 2. The rainfall used to assess the quantity of rooftop rainwater harvesting was the lower figure of 150 mm for a conservative design in line with the arid regions of Jordan and to allow for dry summer months. The average daily temperatures range from 30 °C high in summer to 10 °C low in winter (see Fig. 3). The root-zone sewage treatment plant proposed in one sanitation option in this report is sensitive to ambient temperatures and is designed for the average of summer and winter temperatures.

Household survey

A total of 165 surveys were carried out to understand the current water and sanitation landscape in identified peri-urban areas of Al Mafraq. The survey questionnaire asked questions regarding type of housing including the type of roof, water connection, service, quantity and storage, supplementary water,

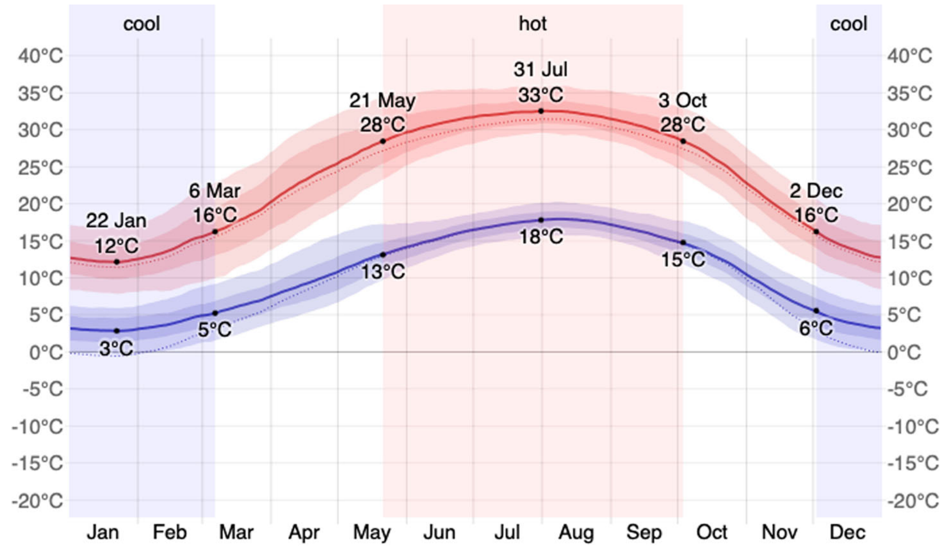

Fig. 3 | Al-Mafraq daily average high (red line) and low (blue line) temperature, with 25th–75th and 10th–90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures. Image source: © WeatherSpark.com.

water treatment, interest in rainwater harvesting and water recycling, toilet facilities, sewage services and/or disposal and how much they paid for services.

The neighbourhood al-Dahiyyah was selected to conduct the surveys based on several factors, including quick and unorganised urban sprawl and sudden population growth since 2011[29], being an area hosting a large number of Syrian refugees, the limited number of studies conducted in the area and its diversity of network connections. Three areas with different levels of connectivity were visited to better understand the neighbourhood's situation:

1. Areas with no connection to water and sewer networks,
2. Areas connected only to water, and
3. Areas connected to water and sewer networks, whether legally or illegally.

It must be noted that connectivity within each of the areas may not be homogenous. While an area was identified as having water and sanitation connectivity overall, not all the households within the selected area may be connected individually.

The selection was supported by observation walks that noted the number of buildings across the three identified areas and conducting 27 semi-structured qualitative interviews to identify the three different levels of water connectivity within the neighbourhood. The neighbourhood was selected to ensure that the survey would capture experiences across these levels of connectivity. A preliminary map of the neighbourhood based on the estimated water and sanitation connectivity was created to purposively sample participants in all the three identified areas.

Satellite imagery was then used to estimate the number of buildings, where ~971 housing units were identified in al-Dahiyyah across the three areas. Based on the number of possible buildings, a sample size of 150 was calculated to conduct the surveys, with 95% confidence level, 11% margin of error and a design effect of 1.5. The survey was carried purposedly on the identified areas within al-Dahiyyah, but participants were selected on convenience sampling once within the areas. The distribution of the sampling quota was based on proportional representation, with a target of 70–30% Syrian-Jordanian respondents respectively. The survey was approved by a UK Research Ethics Committee and a Jordanian Ethics Committee. Written consent was provided by all survey participants. The surveys were administered by MindSet in Arabic in July 2022. Table 1 shows the sampling quota breakdown and the actual respondents per area.

Table 1 | Sampling quota vs actual respondents

	Sampling quota			Actual respondents		
Area	Jordanian	Syrian	Total	Jordanian	Syrian	Total
Green	21	49	70	22	50	72
Yellow	15	35	50	23	36	59
Red	9	21	30	10	24	34
Total	45	105	150	55	110	165
Percentage	30%	70%		33.3%	66.7%	

Design of water and sanitation scenarios

An Excel based decision making tool with adjustable variables was developed, which can be modified by the user to suit the baseline data of unit costs, demographics, climate, etc. for each city to get designs and system costs specific to that city (the tool can be made available upon request). Local unit costs were used to calculate the capital costs and the recurring operational and maintenance costs of the proposed solutions. The assumed unit costs of materials used in the calculations were provided and verified by the authors based in Jordan based on government records.

The scenarios estimate both the capital costs for installing new services and the recurring running and maintenance costs. The two have been brought to the same platform by capitalising the yearly running costs using the prevailing bank interest rate (4.5%) in order to make better comparisons. The cost estimates are normalised on two counts, firstly by using per family cost as the common thread of comparison and secondly by using normalised capitalised costs which take into consideration both the capital expenditure and the O&M lifecycle costs. See Table 2 for the assumptions used to design the systems.

The baseline data used to design the systems (including daily needs, rainfall data and average rooftop areas assumptions) and the technical parameters which are then quantified and costed as per the prevailing prices, as well as typical drawings and images, can be found in the Supporting information.

Cost comparisons of water and sanitation scenarios

In order to make comparisons between options with different capital and running costs, running costs have to be capitalised and added to the initial capital investments, or, alternatively, capital investments can be annualised in terms of interest to be paid on a bank loan and added to operation and maintenance (O&M) costs. Both methods are valid, however, for this work the former was chosen.

The water supply and sanitation systems alternatives were explored across different scales, spanning from house level to city level systems and

Table 2 | Design assumptions

Daily water consumption target	The daily water supply need per capita is targeted at 100 L. This is a little less than the 120–150 L of water per capita provided in some countries to account for more frugal water consumption and takes into account the water scarcity in the region.
Rooftop rainwater harvesting	The quantity of rainwater harvested is based on the annual rainfall value of 150 mm in Al-Mafraq. To allow for evaporation losses, it is assumed that only about 80% of the rainfall received on the roof will be captured. The average rooftop area is conservatively assumed at 100 m^2 per family for rainwater harvesting. This is less than the present terrace area per family calculated from the current density of built form to allow for the future trends in which the multi-story housing is replacing single-story constructions, whereby reducing the rooftop area available for each flat.
House level water tanks	Two house level tank alternatives have been considered. For all water supply options, one is where all dwellings are provided with underground tanks, sized to store water need per family for the duration of the dry period of 6 months as well as rooftop rainwater harvesting. In the option with fully piped and 24-h water supply, an alternative option is also considered where each house only has a small plastic tank to collect the day-to-day rooftop rainwater supplemented by large surface runoff water collection ponds spread across the city to meet the deficiencies in the dry months.
City level elevated and underground water tanks	These have been provided as part of the piped networks on the basis that each tank will serve about 3000 families. The tanks are sized for 1 day water supply, half of which is stored in the underground tank and the other half in the overhead tank above. The elevated tanks are planned sufficiently tall and costed accordingly so that they can supply water at adequate pressures to the houses to avoid pumping at the individual house level.
Design of piped networks	The local piped networks from the elevated water tanks to 3000 families are sized by water flows in them based on daily supply. The pipe diameters and lengths in the cost estimates are based on previous projects designed by the second author with similar water consumptions and development densities[33]. PVC pipes are used as the they are smoother and convey water more economically at smaller diameters at lesser costs. The mains supply pipes from the water sources to the elevated reservoirs are sized larger and, based on the approximate plan dimensions of Al-Mafraq city, it is assumed that on average 5 km of larger diameter pipe length per tank would be required to interconnect them.
Assumed sewage and sludge quantities	Based on the daily water supply per capita of 100 L, the sewer networks and the appurtenances are designed 80% of the water consumption (i.e. 80 L/capita.day). In addition, for Options 1 and 2, it is assumed that the 30 L of sludge is generated per capita every year.
Septic tanks	House level septic tanks are sized for 1-day storage of sewage and 5 years of sludge, assuming an average of 5.3 persons per family. These tanks, therefore, need to be desludged once in 5 years. The cluster level septic tanks are sized for 1-day storage of sewage and 1 year of sludge assuming 250 families connected to the cluster with an average of 5.3 persons per family.
Soakpits	Both the house level and the cluster level soakpits are constructed in honeycomb masonry and sized such that their surface areas in contact with the surrounding soil are adequate to absorb each day's output assuming soil percolation rate of 600 L/d for each square metre of contact area with a safety factor of 3. The wall thicknesses of the soakpits are designed to keep the hoop stresses in brickwork from the soil pressure under the permissible limits of 0.75 N/mm^2.
Sludge bed sizing	Each sludge bed is sized to store sludge output of 5000 families over a span of 1 year to allow for adequate time to convert the sludge to fertiliser[34]. The sludge bed is divided in compartments to permit a continuous turnaround of incoming sludge and outgoing fertilisers.
Root-zone sewage treatment plant	The area of reed bed root-zone treatment plant is sized such that the sewage flowing through it has adequate retention time for the biological oxygen demand (BOD) of sewage to reduce from 300 BOD at entry to river discharge quality of 30 BOD at the outfall[35] (according to the JS 893–2021, this is allowable for irrigation purposes and discharge into surface water ways but not allowable for groundwater recharge[36]). The width to the plant is derived from Darcy's equation of channel flow to ensure that the sewage flow remains submerged below ground to avoid bad smell (refer to Supporting information). The plant is designed for the mean of summer and winter average temperatures to ensure that it works well over the year.
Design of sewer networks	The cluster level piped networks in Option 2 are sized by sewage and sullage flows based on 100 L/capita.day water supply. The pipe diameters and lengths used in cost estimates are based on numerous projects previously designed by the second author with similar water consumptions and development densities, assuming the city topography has reasonable slopes. PVC pipes are used as they are smoother and achieve flushing velocities at of 0.6 m/s at lower slopes with lesser costs to ensure that they do not get blocked.

using alternative technologies for Al-Mafraq, Jordan. The water supply and sanitation scenarios were chosen through a series of team workshops which included collaborators and partners from Jordan. Under the acknowledgment that UN Habitat and other organisations are keen to prioritise Nature Based Solutions[32] and that every drop counts, the team included rainwater harvesting to explore the critical need to conserve and optimise all water resources in a water scarce region as well as to understand whether it could contribute to covering full demand.

Water supply scenarios

For water supply options, approaches currently prevalent in Jordan (vendor supply, piped water and occasionally rooftop harvesting) were combined in various proportions. In the fully piped option with rooftop harvesting, city level water ponds were also added to replace the expensive underground storage tanks and to collect surface runoffs. All the piped water network options include the costs of pumping from the water sources and/or the storage ponds to underground and elevated water reservoirs provided across the city in order to supply water to the households on daily basis and at adequate pressure to avoid house level pumping.

The following four options were chosen for water supply, spanning across scales and technologies:

- **Option 1**: Decentralised approach of purchasing water from vendors supplemented by rainwater harvesting with underground water tank in each house. For households currently not connected to piped water supply, this reflects the reality where most of the water needs are met through vendors.
- **Option 2**: Mixed approach of meeting 50% of the daily need from local piped networks and 50% through purchase of water from vendors supplemented by rainwater harvesting with underground water tank. In areas of the city where water is only supplied for few hours in the day this reflects the reality where residents often use hybrid solutions.
- **Option 3**: Centralised city level piped water supply water to meet 100% of household water needs supplemented by rainwater harvesting with underground water tank This is true for some part of the city and also aspirational for new developments.
- **Option 4**: Centralised city level piped water supply water to each house to meet all the water needs supplemented by a much smaller and cost-effective small plastic tank to support rainwater harvesting. This is an aspirational scenario for future development. In addition to household level measures, in this scenario the large house level underground tanks are replaced by surface runoff water collection ponds spread across the city to support ground water recharge.

Table 3 | Breakdown of capital costs and the recurring operational and maintenance costs for the water supply scenarios

OPTION 1: ROOFTOP HARVESTING & UG TANK + PRIVATE VENDOR SUPPLY AT 94 Lpcd				
		Capital	O&M	Total
Cost of installing house level 100 m^3 underground tank		6060		
Purchase of water from private vendors capitalised			10,102	
COST PER FAMILY JOD		6060	10,102	16,162
OPTION 2: ROOFTOP HARVESTING & UG TANK + PIPED WATER SUPPLY 47 Lpcd + VENDOR SUPPLY				
Note: Cost of piped network & pumping for 47 Lpcd is 75% of 94 L		Capital	O&M	Total
Cost of installing house level 100 m^3 underground tank		6060		
Purchase of 1/2 the water from private vendors capitalised	50%[a]		5051	
47 Lpcd house level water supply network and pumping	75%[b]	341	270	
Add to above for extras e.g. special fittings, valves, metres etc.	25%[c]	85		
Cost of city UG & OH tanks to store water & increase pressure	50%[d]	17	167	
COST PER FAMILY JOD		6503	5488	11,991
OPTION 3: ROOFTOP HARVESTING & UG TANK + PIPED WATER SUPPLY 94 Lpcd				
		Capital	O&M	Total
Cost of installing house level 100 m^3 underground tank		6060		
94 Lpcd house level water supply network and pumping		455	360	
Add to above for extras e.g. special fittings, valves, metres etc.	25%	114		
Cost of city UG & OH tanks to store water & increase pressure		33	333	
COST PER FAMILY JOD		6662	693	7355
OPTION 4: ROOFTOP HARVESTING & SMALL PLASTIC TANK + PIPED WATER SUPPLY 94 Lpcd				
		Capital	O&M	Total
Cost of installing house level 1.5 m^3 rainwater harvesting tank		236		
Cost of city level storm runoff collection ponds		294	109	
94 Lpcd house level water supply network and pumping		455	360	
Add to above for extras e.g. special fittings, valves, metres etc.	25%	114		
Cost of city UG & OH tanks to store water & increase pressure		33	333	
COST PER FAMILY JOD		1132	802	1934

[a]50% for private vendors in option 2 is because only half of 94 L (i.e. 47 L) is supplied by vendors compared to option 1.
[b]75% network and pumping cost in option 2 is in comparison to options 3 & 4 as these pipes have only half the flow. When the flow is halved, the network cost does not halve but reduces by square of half (i.e. 25%), hence 75% is used.
[c]25% of the network cost for each option is added to allow for fittings, valves and metres based on the norms we have observed across a large number of water supply projects designed by us.
[d]50% for UG/OH tanks in option 2 is in comparison to options 3 & 4 as only half of 94 L (i.e. 47 L) is supplied through piped networks.
The O&M are the annual running and maintenance costs which then have been capitalised as per the prevailing bank interest rates.

Regarding rainwater harvesting, based on an average rooftop area of 100 m^2 per family times 150 mm of annual rain with 80% of the terrace water reaching the tank, the total rainwater that can be collected is 12 m^3 per family per year. This divided by 365 days in a year and 5.3 persons per family comes to 6 L per capita per day (Lpcd), i.e. 6% of the targeted need of 100 Lpcd.

Table 3 shows the breakdown of capital costs and the recurring costs for operation and maintenance of the water supply scenarios and Fig. 4 shows a chart with the capitalised costs of the water supply systems.

Sanitation Scenarios

For sanitation, options across the scale ranging from house level treatment to sewerage with community treatment to city level networks were used as well as conventional treatment using solutions prevalent in Jordan. For the city level, a new option of root-zone treatment plant in lieu of conventional treatment was also added given its low cost, low maintenance and the potential for water recovery. The following four options were chosen for sewerage, spanning across scales and technologies.

- **Option 1**: Decentralised approach of individual septic tank/cesspit and soakpit treatment at each house served by sludge beds, each serving 5,500 families, spread across the city. House level treatment is currently the only option in the areas not covered by sewer networks and is commonly found in parts of Jordan.
- **Option 2**: An intermediate cluster approach of 250 houses connected by a local sewer network connected to common septic tank and soakpits served by sludge beds, each serving around 20 clusters (5500 families), spread across the city. This approach introduces sewer networks in areas of the cities lacking them, such as peri-urban settlements and reduces per house treatment costs.
- **Option 3**: City level sewerage networks connected to conventional activated sludge treatment plant.
- **Option 4**: City level sewerage networks connected to root-zone sewage treatment plants, each plant serving 5500 families and placed close to water supply sources. Of the many treatment plant options available, root-zone method was deliberately chosen as it a simple and natural system not requiring sophisticated mechanical and electrical inputs. This option does not need separate sludge beds as the plant roots manage to break down the sludge in sewage. Further, with appropriate design, the sewage water can be treated in this technology to river discharge standards and recycled back into the system to significantly supplement the water supply in this water scarce country.

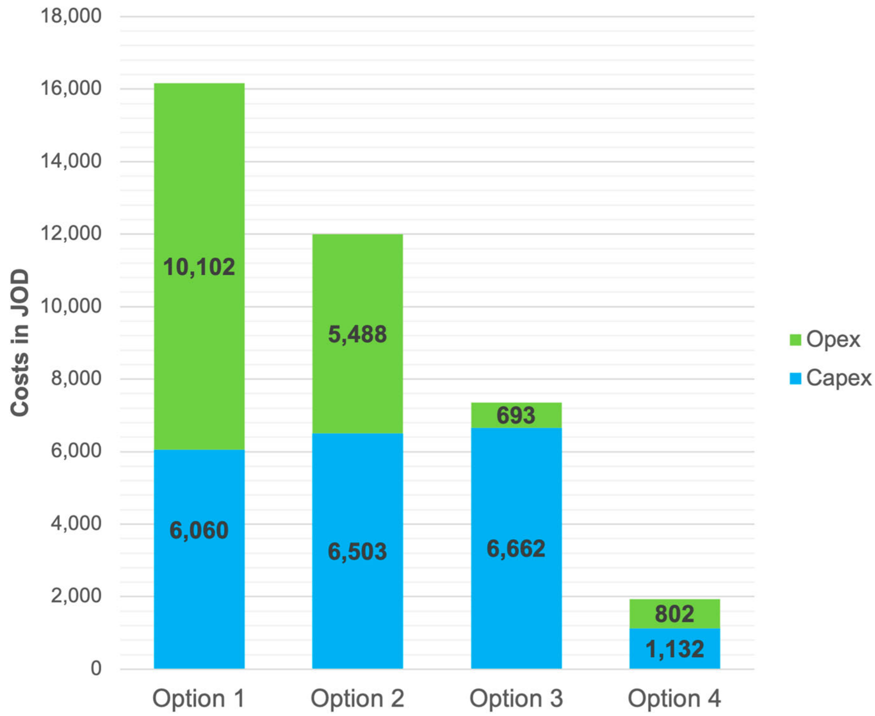

Fig. 4 | Capitalised costs of water supply systems.

Table 4 | Breakdown of capital costs and the recurring operational and maintenance costs for the sanitation scenarios

OPTION 1: HOUSE LEVEL SEPTIC TANKS AND SOAKPITS			
	Capital	O&M	Total
Cost of individual house connections to septic tanks	102		
Cost of house level septic tank and soakpit	618		
Cost of sludge bed and desludging septic tank capitalised	6	440	
COST PER FAMILY JOD	726	440	1167
OPTION 2: HOUSES CONNECTED TO COMMUNITY SEPTIC TANKS AND SOAKPITS			
	JOD	O&M	Total
Cost of individual house connections to cluster level sewer lines	102		
Cost of community level septic tank and soakpits	143		
Cost of local sewerage lines to community septic tank	437	173	
Cost of sludge bed and desludging septic tank capitalised	6	307	
COST PER FAMILY JOD	688	480	1168
OPTION 3: CITY WIDE SEWERAGE NETWORK WITH CONVENTIONAL TREATMENT PLANTS			
	Capital	O&M	Total
Cost of individual house connections to city sewerage network	102		
Cost of city sewerage network	559	216	
Cost of conventional sewage treatment plant	48	1458	
COST PER FAMILY JOD	709	1674	2383
OPTION 4: CITY WIDE SEWERAGE NETWORK WITH ROOT-ZONE TREATMENT PLANTS			
	Capital	O&M	Total
Cost of individual house connections to city sewerage network	102		
Cost of city sewerage network	559	216	
Cost of root-zone treatment plants	102	109	
COST PER FAMILY JOD	763	325	1088

The O&M are the annual running and maintenance costs which then have been capitalised as per the prevailing bank interest rates.

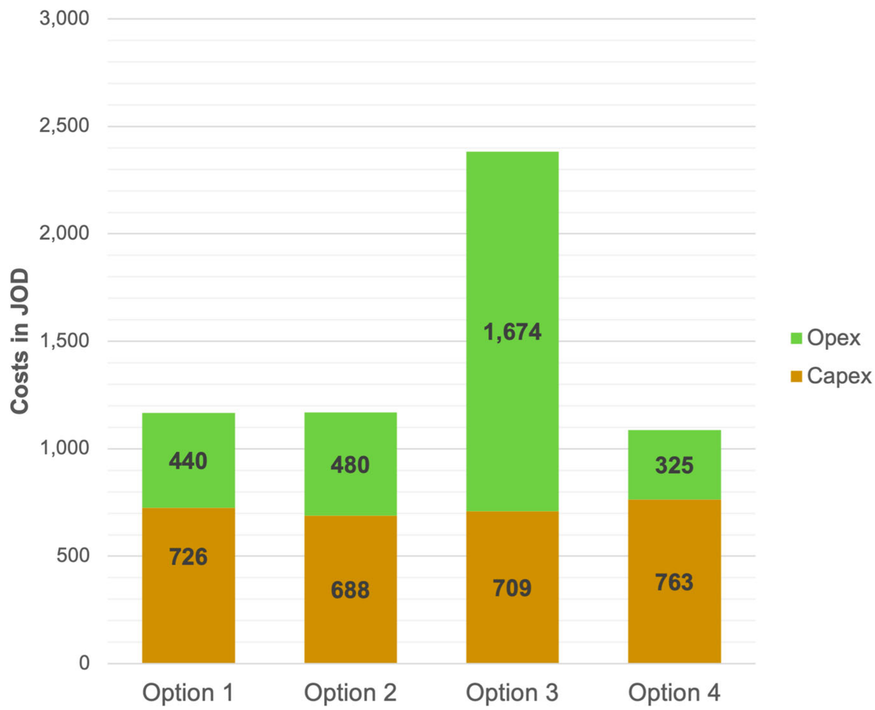

Fig. 5 | Capitalised costs of sanitation systems.

Table 4 shows the breakdown of capital costs and the recurring costs of operation and maintenance of the sanitation scenarios and Fig. 5 shows a chart with the capitalised costs of the sanitation systems.

Data availability

The datasets used and/or analysed during the study are available from the corresponding author on reasonable request.

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Author contributions
M.G.R. contributed to processing the data, performing the analysis, interpreting the results and drafting the manuscript; H.P. contributed to the methodology, processing the data, performing the analysis, interpreting the results, designing the figures and worked on the manuscript; L.C. contributed to the design and implementation of the research and supervised the work; S.T. contributed to the design and implementation of the research and aided in interpreting the results; P.P. contributed to the design and implementation of the research, aided in interpreting the results, supervised the work and worked on the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Competing interests
The authors declare no competing interests.

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