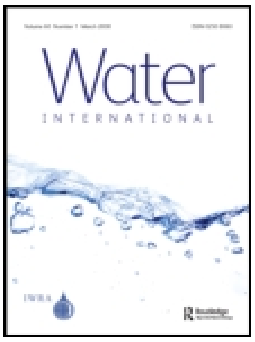

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Impacts of supply duration on the design and performance of intermittent water distribution systems in the West Bank

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This paper analyzes the intermittent water distribution system in the West Bank, Palestine. It quantifies the impacts of reduced supply duration on the hydraulics and costs of water distribution. It shows that designing systems based on intermittent supply criteria implies increasing the diameters of pipes significantly, which is expensive and infeasible. The paper recommends that studying the local conditions should precede the design of new systems to avoid reduced supply duration and related negative impacts. In addition, improving governance, revising tariffs, reducing leakage, saving water, involving the private sector, and improving water diplomacy should be considered in any water policy reform.

Keywords: continuous distribution; intermittent distribution; costs; hydraulics; water policy reform; water supply

Introduction

Ensuring sufficient water is one of the most fundamental challenges to sustainable development, economic growth and political stability in the Middle East in general and in the Palestinian Territory in particular. Water security is critical to the viability of the anticipated Palestinian state, where the long-term challenge for Palestinian policy makers, water planners and engineers is to ensure sufficient and reliable water supplies under severe conditions (Abu-Madi, 2010). According to the Palestinian Water Authority (PWA, 2012), nearly 450 localities in the West Bank (all the urban areas and 96% of the rural areas) are connected to piped water networks. However, the Palestinian achievement in meeting the water supply coverage target of the Millennium Development Goals has been seriously undermined by the quality of service and unreliability of water supplies represented by the intermittent and insufficient water supply. Water supply frequency to most of the existing water distribution systems is limited to a few hours per day or a few days per week, which is attributed to: (1) restricted access to the groundwater resources as a result of political dispute between the Israelis and the Palestinians over the water resources (Selby, 2013; World Bank, 2009); (2) poor design and high unaccounted-for water; (3) rising water demand; (4) insufficient financial resources, and reliance on foreign aid for implementation of new projects and rehabilitation of existing old ones; and (5) discrepancy in water tariffs in the

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different governorates of the West Bank, where tariffs are low and do not cover even the recurring costs (PWA, 2012).

The political conflict between Palestinians and Israelis exacerbates the water-related problems. Palestinians do not have full control over their groundwater resources, which are shared with Israel. Groundwater aquifers are the major sources of water for Palestinian localities and Israeli settlements in the West Bank. Israel imposes restrictions on Palestinians regarding construction of new groundwater wells and limits abstraction rates from the existing wells. According to Article 40 of the Oslo II interim agreement between the Palestinians and the Israelis (Negotiations Affairs Department, 1995), the allocation of water resources of the three shared aquifers restricts Palestinian abstraction to 22 million m^3 annually from the Western Aquifer, 42 million m^3 from the North-Eastern Aquifer, and 54 million m^3 from the Eastern Aquifer (PWA, 2012).

The main accessible water sources for the Palestinians living in the West Bank are groundwater, springs, and water purchased from Israeli's national water company, Mekorot. The main water resources in the Gaza Strip are groundwater from the Coastal Aquifer and desalinated sea water. Currently, the Palestinians do not have access to surface-water resources such as the Jordan River, which is controlled by Israel. Groundwater is pumped from shallow and deep aquifers through agricultural and domestic wells that were constructed during the Jordanian mandate (before 1967). Most of the wells are owned by individual farmers or farmers' cooperatives and are intended for agricultural irrigation. The well owners use part of the produced water for irrigation of their own lands and sell excess water to neighbouring farmers as well as supplying drinking water to towns and villages from their agricultural wells because it is more profitable than selling irrigation water to farmers in these difficult economic conditions (Abu-Madi, 2010).

The total water quantity obtained from different sources in the West Bank was 153.9 million m^3 in 2010: 71.6 million m^3 from local groundwater wells (46.5%), 55.5 million m^3 purchased from Mekorot (36.1%), and 26.8 million m^3 from local springs (17.4%) (PWA, 2012). A total of 85 million m^3 of water was supplied for domestic purposes in the West Bank, provided at a supply rate of 102 litres per capita per day (lcd). Of the 85 million m^3, only 60 million m^3 was actually consumed, leaving an average consumption rate of 73 lcd, which lies below the WHO minimum standard of 100 lcd (PWA, 2012). The average technical losses (leakage) in the West Bank are about 29.4% of the total water supplies (Table 1). The Palestinian population and water demand have grown very fast since the Oslo Accord in 1994, but the allocated amounts of water have not increased.

In 2010, the population of the West Bank was 2,276,000, distributed over 510 localities (cities, towns, villages, and refugee camps) in 11 governorates (Tables 1 and 2). About 80% of the localities have a population of less than 5000, and about 98% of less than 25,000. Intermittent water supplies characterize the existing distribution systems in all Palestinian localities. All the existing distribution systems were designed to provide continuous supply, assuming a supply frequency of 24 hours per day. However, Palestinian municipalities, village councils, and water utilities rely on central storage facilities (public tanks) and divide the cities into a number of zones where water is pumped rotationally between these zones according to an operational schedule. The frequency of water pumping to a given zone could be several hours, or days, or weeks, depending on the local conditions; Table 3 shows an example of water supply frequency in a number of localities of the West Bank. Therefore, many of the public tanks in towns and villages of the West Bank are rarely filled by the end of the water supply period despite their small storage capacity (150–300 m^3).

The water supply systems are unreliable, and consumers do not have regular access to water in the distribution networks, which can be explained by either not enough water being

Table 1. Water consumption rates in the West Bank governorates, 2010.

Governorate	Population (1000s)	Total supplied (10^6 m^3)	Total consumed (10^6 m^3)	Total losses (10^6 m^3)	Percentage losses	Consumption rate (lcd)
Jenin	274	5.987	4.347	1.640	27.6	43
Tubas	55	1.700	1.190	0.510	30.0	60
Tulkarm	166	4.606	2.759	1.847	40.1	46
Nablus	340	11.234	7.920	3.314	29.5	64
Qalqilya	97	4.009	3.087	0.922	23.0	87
Salfit	63	2.567	2.015	0.552	21.5	87
Jericho	45	3.550	2.684	0.866	24.4	162
Ramallah	301	16.195	11.855	4.340	26.8	108
East Jerusalem	145	4.635	2.790	1.845	39.8	53
Bethlehem	189	10.686	7.010	3.676	34.4	102
Hebron	600	19.810	14.620	5.190	26.2	67
Total	2,276	84.979	60.277	24.702	29.4	73

Source: PWA (2012).

supplied at the source or the transmission pipes having small diameters that cannot carry large amounts of water in the short periods of supply. These conditions force people to rely on individual water collection by means of ground or/and roof tanks and to buy water from private vendors at a high price (around USD3–5/m^3). In the cases where ground tanks are used, pumps are needed to provide the necessary energy to elevate the water to the roof tanks.

Most water supply projects are suffering from increased operational costs, low tariffs, and limited revenues. The current water tariffs vary between USD0.5/m^3 and USD1.3/m^3, and the recovery rate is 60–80% (PWA, 2012). Increasing water tariffs does not seem to be an option under consideration due to political complexity and the state of the economy. Failing to recover the operational costs of water supply projects will add to the financial deficiency of those projects and might jeopardize their sustainability.

By tapping water from their individual storage tanks, consumers do not rely on pressure in the distribution system, as long as it is sufficient to refill their tanks during supply periods. Unlike in continuous water supply systems, this creates a smaller range of hourly peak factors, allowing fairly stable supply through the distribution pipes. Therefore, balancing of actual demand occurs for each individual household, whereby replenishing of the volume behaves differently depending on water availability in the distribution network (Trifunovic & Abu-Madi, 1999). Water is consumed according to demand patterns that most of the time do not have an influence on the delivery and supply patterns. The following regimes for water supply, delivery and demand are practiced in the West Bank and some countries of the Middle East (Figure 1):

Continuous supply with continuous delivery (CSCD). This is a typical supply regime in developed countries, in which water is supplied directly and delivered continuously to consumers thanks to availability of water at the source and adequate facilities for transport and distribution. The existence of individual storage tanks (if any) in this case does not influence the hydraulic functions of the continuous-supply design and operation. This means that the supply, delivery and demand patterns are identical.

Table 2. Distribution of Palestinian population in the West Bank.

Population categories (1000s)	Less than 0.5	0.5−1	1−5	5−10	10−15	15−25	25−50	More than 50	Total
Number of localities	3	8	13	17	63	224	68	114	510
Total population	364, 605	296, 956	259, 042	212, 887	469, 272	591, 543	55, 559	26, 303	2, 276, 167

Source: PCBS, (2010).

Table 3. Discrepancy in water supply frequency in rural localities of the West Bank.

Water supply frequency	Localities
Less than 6 hours per day	Dura, Sa'er, Yatta, Doma, Aqraba, Jenin, and many others
8–10 hours per day	Attil, Deir Ghoson, Tubas, Rameen, Qafin, and many others
2 days per week	Abu Qash, Jafna, Deir Al-Sudan, Ajoul, Ein and Senia, and many others
3 days per week	Abu Shakhaidem, Al-Ram, Byrham, Beir Nabala, Dura Al-Qare', Rafat, Attarah, Kobar and many others
4 days per week	Al-Teerah, Beitonia, Al-Jalazoun, Hazma, and Surda, and many others
7 days per week	Parts of Al-Biereh,Nablus, Ramallah, Tulkarem, and Um Safa,

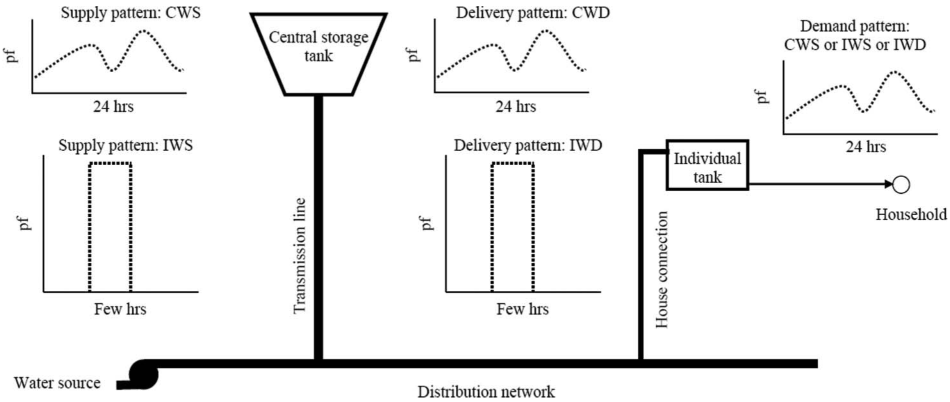

Figure 1. Different regimes of water supply, delivery and demand.

Continuous supply with intermittent delivery (CSID). Here water is delivered to consumers intermittently, despite its continuous supply. This regime is typical when source capacity is limited, e.g. when water is purchased from agricultural wells that limit the duration of water supply to few hours per day. Water shortage at the source and topographic conditions preclude supplying the entire town or city at the same time. In these cases, the distribution networks are divided into several pressure zones, through which water is delivered alternately; i.e. each supply zone experiences intermittent water delivery. This means that the supply, delivery and demand patterns are different. This regime is typical in Al-Bireh, Amman, and Ramallah, where the water is pumped continuously from aquifer wells but its delivery to consumers alternates intermittently depending on the capacity of supply facilities and water demand.

Intermittent supply with continuous delivery (ISCD). Thanks to scheduled access to the water source and availability of central storage facilities of adequate capacity, water is delivered to consumers continuously, despite its intermittent supply. This means that the supply and delivery patterns are different, while the demand and the delivery patterns are identical. This regime is typical in small towns and villages that are equipped with adequate storage facilities (elevated tanks) and supplied with water from agricultural wells. In these cases, the few supply hours are sufficient to fill the elevated tank and most of individual storage tanks. The water consumed from the individual storage tanks is directly compensated from the pressurized distribution network; thus in this case storage does not have major hydraulic impact.

Intermittent supply with intermittent delivery (ISID). With scheduled access to the water source and central storage facilities of inadequate capacity, both water supply and its delivery to consumers are intermittent. This means that the supply, delivery and demand patterns are different. Furthermore, water shortage and topographic conditions force engineers to divide the distribution networks into several pressure zones, through which water is delivered alternately. This regime is typical in most of the small towns and villages, which are equipped with inadequate storage facilities (elevated tanks) and supplied with water from agricultural wells. Hence, the few supply hours are not sufficient to fill the elevated tanks and/or individual storage tanks. During the off-supply time, water is consumed directly from the individual tanks, to be compensated when the distribution network is pressurized again. In such cases, the individual storage tanks play a significant role in the hydraulics of water distribution.

Therefore, the design of water transport and distribution systems under intermittent conditions should not be based on the minimum and maximum peaks of the demand pattern but on the peaks of supply and delivery patterns that are governed by availability of sufficient water at the source, the capacity of the supply system, and the number of supply and delivery hours.

The case of the West Bank is a typical example of the intermittent supply systems that are widely used in most developing and some developed countries that endure water shortage. This system is common in Africa (Khatri & Vairavamoorthy, 2007; Vairavamoorthy, Gorantiwar, & Mohan, 2007), the Middle East (Abu-Madi, 1996; Al-Ghamdi, 2010; Rosenberg & Lund, 2009; Rosenberg, Tarawneh, Abdel-Khaleq, & Lund, 2007, 2008; Trifunovic & Abu-Madi, 1999), Europe (De Marchis et al., 2010), South-East Asia (Choe, Varley, & Bijlani, 1996; McIntosh, 2003; Sanjay & Dahasahasra, 2007; Yepes, Ringskog, & Sarkar, 2001), and the United States (Renwick & Green, 2000). There are many calls for transforming intermittent water supply in the developing countries into continuous supply (McIntosh, 2003; Sanjay & Dahasahasra, 2007; Totsuka, Trifunovic, & Vairavamoorthy, 2004; World Bank, 2004). Nevertheless, and despite the potential risk of water contamination, intermittent supply remains the only possibility for many countries (Abu-Madi, 1996; Al-Ghamdi, 2010; Trifunovic, 2006).

Vairavamoorthy, Akinpelu, Lin, and Ali (2001) argued that there is an implicit assumption in the literature they studied that the design procedure used in developed countries is appropriate for developing countries. Indeed, water engineers in the Palestinian Territory often design their water distribution networks assuming continuous-supply conditions, while in reality they experience intermittent conditions. The guidelines and criteria for the design of water supply systems focus on the hourly, daily and monthly demand patterns. For example, the guideline for design of water distribution systems developed by the Palestinian Water Authority (PWA, 2003) is based on continuous-supply criteria, though all its networks experience intermittent distribution. The PWA guideline suggests that hourly, daily and monthly maximum peaking factors are 1.10, 1.10 and 1.25, respectively. It limits the network pressure to 20 mwc at minimum peaks and to 60 mwc at maximum peaks. It recommends pressure zoning where topography varies considerably. These are ideal guidelines for design of continuous water distribution systems in water-rich countries.

The main consequences of operating a water distribution system under intermittent supply conditions that was originally designed for 24-hour continuous supply are: (1) pumps and pipes failing to carry the required water demand during short periods, thus leading to unreliable service and uneven distribution of water; (2) low pressure due to increased hydraulic losses associated with increased flows and undersized pipe diameters; (3) high energy losses, leading to increased operational costs; (4) increased water leakage; and (5) high coping costs, because consumers have to pay for storage and pumping in addition to purchasing expensive water from private vendors as well as bottled water. Technically, these problems can be mitigated or eliminated if the intermittent supply conditions are considered while designing the water distribution systems. Izquierdo, Montalvo, Perez-Garcia, and Matias (2012) assume that, in the practice of engineering decision making, politicians, economists, engineers and environmental specialists are involved in final decisions. Therefore, the design of a water distribution system involves finding acceptable trade-offs among a mixture of incompatible objectives, such as minimizing capital and operational costs, fulfilling water demands, adhering to hydraulic complexity and design constraints, and guaranteeing a certain degree of reliability (Goulter & Bouchart, 1990; Walski et al., 2003).

The aim of this paper is to study the various impacts of supply duration on water distribution systems under intermittent conditions, and to provide a way forward for Palestinian water planners and policy makers to improve the water supply sector.

Methodology

Calculation of water demand and optimal pipe diameter

Water demand calculations are made for six categories of small and medium-size Palestinian localities, based on a specific water consumption of 100 lcd: A (25,000 inhabitants), B (15,000), C (10,000), D (5000), E (1000) and F (500). The iteration procedure described below is used for the calculation of optimal pipe diameter D (Larock, Jeppson, & Watters, 2000; Trifunovic, 2006; Walski et al., 2003). The input data in calculations are pipe length L, pipe roughness k, flow Q, hydraulic gradient ($\Delta H/L$ or S), and temperature T.

(1) Assume the initial velocity.
(2) Calculate the diameter D from the flow/velocity relation:

$$D^2 = \frac{4Q}{v\pi} \tag{1}$$

(3) Calculate the Reynolds number (Re) that describes the flow regime:

$$\mathrm{Re} = \frac{vD}{\upsilon} \tag{2}$$

(4) Determine the friction factor λ using the appropriate friction-loss equation or Moody diagram based on the Re and k/D values.
(5) Calculate the velocity v:

$$v = -2\sqrt{2gDS}\,\log\left[\frac{2.51\upsilon}{D\sqrt{2gDS}} + \frac{k}{3.7D}\right] \tag{3}$$

(6) If the assumed and determined velocities differ substantially, repeat steps 2–5, taking the calculated velocity as the new input, until reaching a sufficient accuracy.
(7) Round the calculated diameter to the next-higher commercial size.

The results are presented as relations between water supply duration and pipe diameters (calculated and commercial) for different population categories.

Investment costs

The total investment costs for steel pipes were collected for different pipe diameters from the records of contractors and municipalities. These investment costs include prices and installation of pipes, valves and other fittings. These costs are drawn against a series of water supply periods for different population categories of localities. A relation is established between commercial pipe diameters and per-unit costs.

Energy costs

The Darcy-Weisbach hydraulic head loss (Equation (6)) and annual cost of energy wasted over supply duration (Equations (4) and (5)) are calculated per unit of pipe length (Larock et al., 2000; Trifunovic, 2006; Walski et al., 2003); the pipe diameter is held constant at optimal commercial diameter for each population category, while the pipe flows are changed according to the number of water supply hours:

$$E = \frac{\rho g Q \Delta H}{1000 \times 3600} \frac{t}{\eta} e \quad (4)$$

$$\varepsilon = \frac{E}{L} = \frac{9.81 \times Q \Delta H}{3600 \times L} \frac{e}{\eta} \times 365 \times t \approx Q \times t \frac{e}{\eta} \frac{\Delta H}{L} \approx Q \times t \times S \frac{e}{\eta} \quad (5)$$

$$\Delta H = h_{\mathrm{f}} = \frac{\lambda L}{2g} \frac{v^2}{D} \quad (6)$$

where ρ = density of water (1,000 kg m^{-3}); g is the gravitational constant (9.81 m s^{-2}); E = annual energy loss (kWh); Q = pipe flow (m^3/h); ΔH = head loss (mwc); t = supply duration (1–24 hours); η = corresponding pumping efficiency (assumed to be 75%); e = unit price of energy (USD0.15/kWh); ε = annual cost of energy loss per meter length of pipe (USD m^{-1} y^{-1}); L = pipe length (m); S = hydraulic gradient = $\Delta H/L$ (mwc/km); h_{f} = friction loss (mwc); and λ = friction factor.

The pipe diameters and corresponding energy consumption and hydraulic gradient are drawn against a series of water supply hours.

Results and discussion

Impact of supply duration on water demand and pipe diameter

Under CSCD conditions, the demand multiplier is one. The consumers will – in some way or another – collect part of their water needs regardless of the water supply duration because they rely on their individual storage facilities. The major challenge is imminent when there are restrictions on the duration of water supply or delivery, as described earlier in the cases of CSID, ISCD, and ISID.

Under intermittent-supply conditions, halving the supply duration (from 24 to 12 hours per day) doubles the demand multiplier to 2 (Table 4 and Figure 2). The demand multiplier increases to 3 when the supply duration drops to 8 hours per day, and to 6 at 4 hours per day. Reducing the supply duration to 3 hours per day increases the demand multiplier to 8; at 2 hours per day it goes to 12, and at 1 hour per day the demand multiplier is 24. Thus, water supply duration has a strong effect on the demand multiplier or peak factor: pf = $24.0/t$, where t is the water supply duration in hours per day (Figure 2). Therefore, consequent to reductions in supply duration, water supply systems designed for continuous-supply conditions will face serious problems.

Flow variations as a result of intermittent supply conditions influence optimal pipe diameter. Reducing the supply duration will necessitate increasing the pipe diameter to meet the total water demand of the locality. The results show that the impact of supply duration on pipe diameter is relatively low in the case of small localities compared to large ones (Figures 3 and 4). For example, in a small locality of 5000 inhabitants, the main water transport pipeline under continuous supply conditions should have a diameter

Table 4. Effect of supply duration on water demand and optimal pipe diameter for different population categories.

Category (population)		A (25,000)		B (15,000)		C (10,000)		D (5,000)		E (1,000)		F (500)	
Supply duration (hours)	pf	Q^a (L/s)	D^b (mm)	Q (L/s)	D (mm)	Q (L/s)	D (mm)	Q (L/s)	D (mm)	Q (L/s)	D (mm)	Q (L/s)	D (mm)
24	1.00	28.94	191	17.36	157	11.57	135	5.79	104	1.16	57.3	0.58	44.3
23	1.04	30.19	194	18.12	160	12.08	137	6.04	106	1.21	58.2	0.60	45.0
22	1.09	31.57	197	18.94	163	12.63	140	6.31	108	1.26	59.1	0.63	45.8
21	1.14	33.07	201	19.84	165	13.23	142	6.61	110	1.32	60.2	0.66	46.6
20	1.20	34.72	204	20.83	169	13.89	145	6.94	112	1.39	61.3	0.69	47.4
19	1.26	36.55	208	21.93	172	14.62	148	7.31	114	1.46	62.4	0.73	48.3
18	1.33	38.58	213	23.15	175	15.43	151	7.72	116	1.54	63.7	0.77	49.3
17	1.41	40.85	217	24.51	179	16.34	154	8.17	119	1.63	65.1	0.82	50.4
16	1.50	43.40	222	26.04	183	17.36	157	8.68	121	1.74	66.6	0.87	51.5
15	1.60	46.30	228	27.78	188	18.52	161	9.26	124	1.85	68.2	0.93	52.7
14	1.71	49.60	234	29.76	193	19.84	165	9.92	128	1.98	69.9	0.99	54.1
13	1.85	53.42	240	32.05	198	21.37	170	10.68	131	2.14	71.9	1.07	55.6
12	2.00	57.87	248	34.72	204	23.15	175	11.57	135	2.31	74.1	1.16	57.3
11	2.18	63.13	256	37.88	211	25.25	181	12.63	140	2.53	76.5	1.26	59.1
10	2.40	69.44	265	41.67	219	27.78	188	13.89	145	2.78	79.3	1.39	61.3
9	2.67	77.16	276	46.30	228	30.86	195	15.53	151	3.09	82.4	1.54	63.7
8	3.00	86.81	289	52.08	238	34.72	204	17.36	157	3.47	86.1	1.74	66.6
7	3.43	99.21	304	59.52	250	39.68	215	19.84	165	3.97	90.5	1.98	69.9
6	4.00	115.74	322	69.44	265	46.3	228	23.15	175	4.63	95.9	2.31	74.1
5	4.80	138.89	345	83.33	284	55.56	244	27.78	188	5.56	102.7	2.78	79.3
4	6.00	173.61	376	104.17	310	69.44	265	34.72	204	6.94	111.6	3.47	86.1
3	8.00	231.40	419	138.89	345	92.59	296	46.30	228	9.26	124.3	4.63	95.9
2	12.00	347.22	489	208.33	403	138.89	345	69.44	265	13.89	144.7	6.94	111.6
1	24.00	694.44	637	416.67	524	277.78	449	138.89	345	27.78	187.8	13.89	144.7

[a] Average specific consumption = 100 lcd; $T = 10$ °C; $S = 0.005$ m/km; $k = 0.05$ mm.
[b] These are calculated pipe diameters. Commercial pipe diameters are 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, and 650 mm.

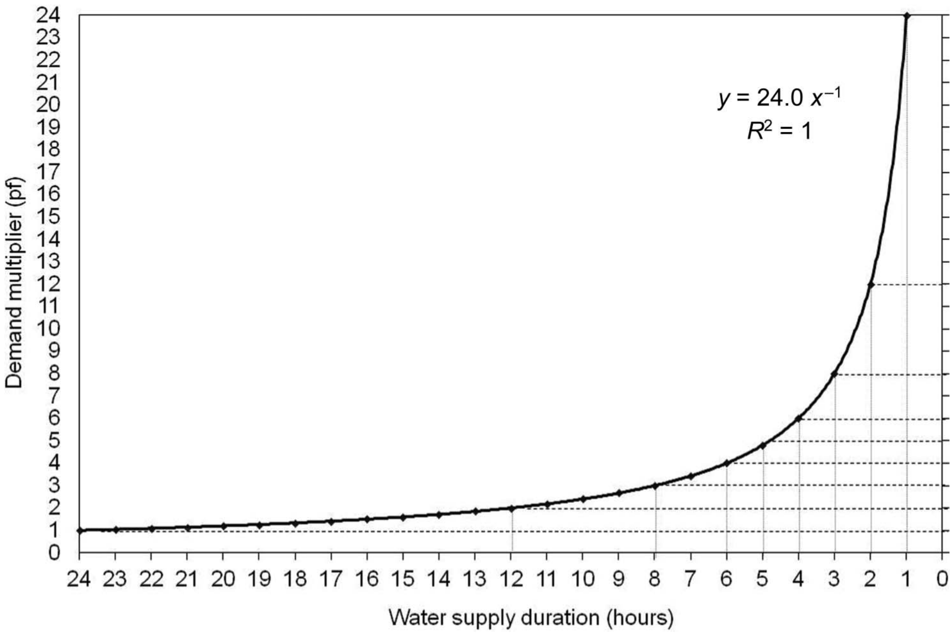

Figure 2. Water supply duration and demand multiplier (peak factor).

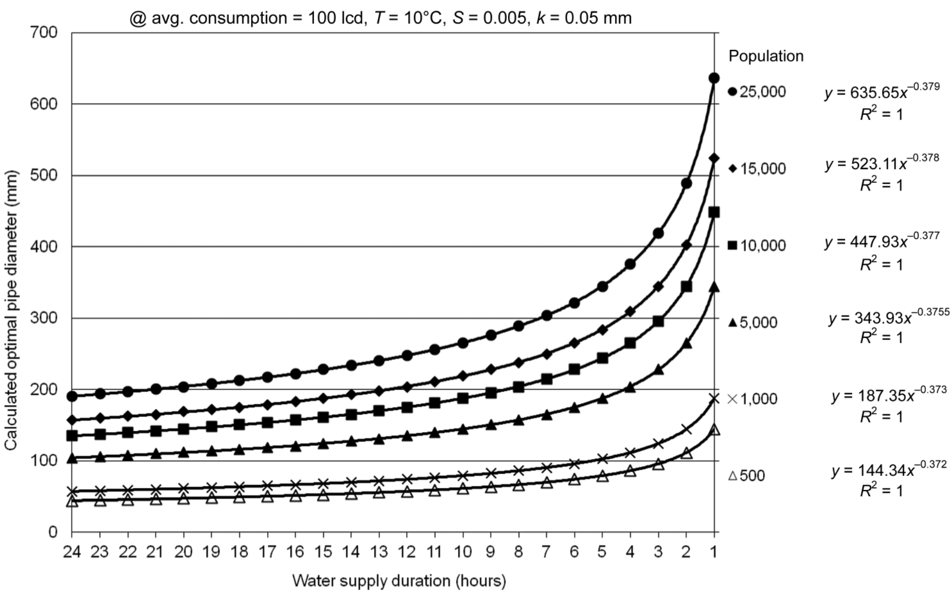

Figure 3. Water supply duration and calculated optimal pipe diameter for different population categories.

of 150 mm. Under intermittent conditions, reducing the supply duration by 14 hours per day does not necessitate increasing pipe diameter; 150 mm is sufficient. But reducing the supply duration by 15–19 hours per day necessitates increasing the pipe diameter to 200 mm. Reducing the supply duration by 20–21 hours per day necessitates increasing the

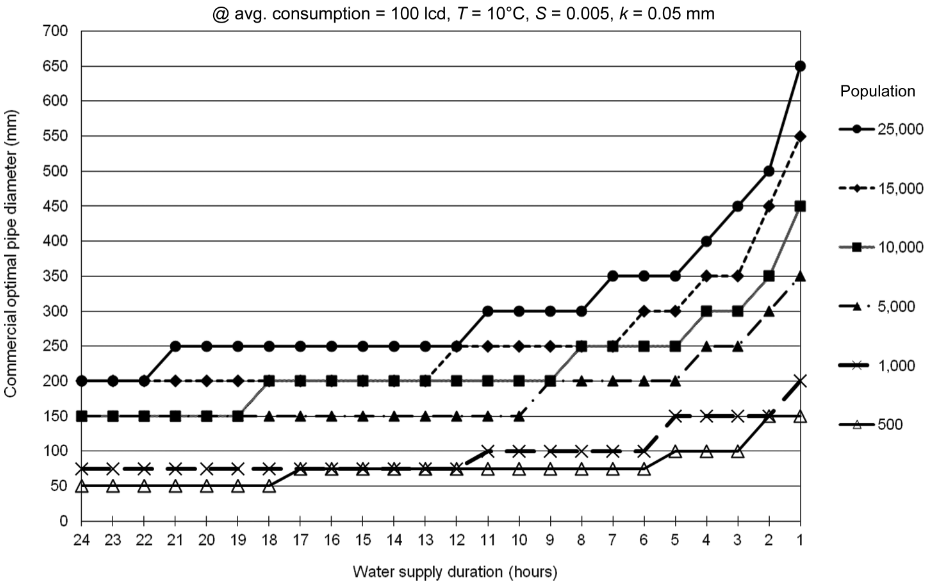

Figure 4. Water supply duration and optimal commercial pipe diameter for different population categories.

pipe diameter to 250 mm. Reducing the supply duration by 22 hours per day necessitates increasing the pipe diameter to 300 mm. Reducing the supply duration by 23 hours per day necessitates increasing the pipe diameter to 350 mm. In the case of a medium-sized locality of 25,000 inhabitants, under continuous water supply conditions, the main water transport pipeline needs to have a diameter of 200 mm. Reducing the supply duration from 24 to 3–12 hours per day necessitates increasing the pipe diameter to 250 mm. Reducing the supply duration by 13–16 hours per day necessitates increasing the pipe diameter to 300 mm. Reducing the supply duration by 17–19 hours per day necessitates increasing the pipe diameter to 350 mm. Reducing the supply duration by 22 hours per day necessitates increasing the pipe diameter to 500 mm.

Water distribution systems in large localities are more sensitive to reductions in water supply duration than those in small towns and villages. Similarly, intermittent-supply conditions have a greater impact on the main transmission pipes (ISCD and ISID) than the distribution network (CSID). In other words, the impact of reduced supply duration increases with proximity to the water source and decreases with proximity to the consumer.

These results prove that reducing the supply duration is a major factor that leads to insufficient water availability for consumers and causes unreliability of the existing distribution systems. These challenges will be exacerbated if the current design practices overlook this fact and assume water availability and appropriateness to provide continuous water supplies. Studying the local conditions of water availability is a necessary step before embarking on the design of new water supply systems to avoid reduced supply duration and the resulting negative impacts. As a result, increased demand multipliers will require increasing the diameters of pipes and capacity of public storage tanks, and thus, construction costs will increase substantially, under the existing conditions of limited financial resources.

Impact of intermittent conditions on hydraulic gradient and network pressure

Low water pressure within households, a major shortcoming of individual storage, is due to the small elevation difference between the roof tank and the water tap inside the house. Therefore, consumers do not benefit from the high pressure in the distribution network, as long as it is sufficient to deliver water and refill their individual tanks. Pressure inside low-rise buildings does not exceed 15 mwc (typical tank elevation is 15 m) in best practices. In multi-storey buildings, where a large number of residential flats share the same roof, pressure for consumers on the top floor is low compared to on the ground floor.

The total energy loss per unit length of pipeline, known as hydraulic gradient ($S = \Delta H/L$), depends strongly on water demand or flow. Hydraulic gradient is an indicator of energy consumption and a major part of the recurring costs of water supply systems. Good design practices recommend that the hydraulic gradient not exceed 10 m/km. Lower values indicate minimized energy losses and reduced operational costs, as will be discussed in the next section. Under intermittent-supply conditions, the existing pipelines will have to carry different water quantities depending on the number of supply hours. This leads to increased friction losses (ΔH) or hydraulic gradient (S) and reduced network pressure, and therefore will not fulfil the water demand of all consumers. For example, halving the supply duration in a 200-mm-diameter pipeline ($k = 0.05$ mm at 10 °C) increases required flow from 33 L/s to 60 L/s, thus increasing the hydraulic gradient from 5 m/km to 15 m/km (Figure 5) – a 10 mwc/km reduction in initial network pressure. Further reductions in supply duration will necessitate substantial increases of the flow and therefore energy losses in the pipeline. As a result of reduced network pressure, service will be unreliable: water will fail to reach many consumers, especially those located at higher elevations of the network.

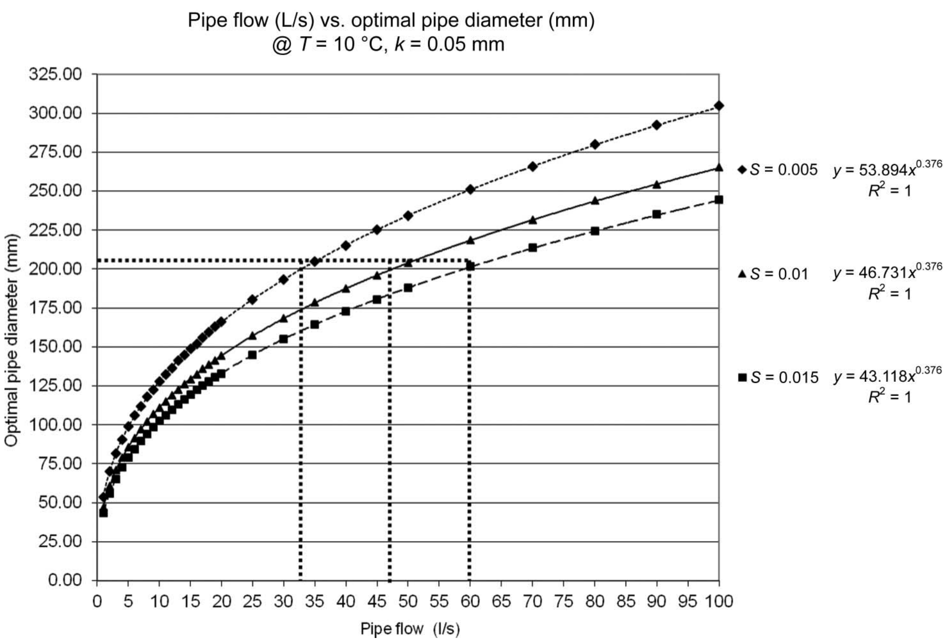

Figure 5. Impact of increased pipe flow on hydraulic gradient.

Impact of supply duration on water transport costs

The impacts of supply duration on the costs of water transport and distribution will be high in large localities because any change to water demand substantially impacts pipe diameter. In small localities, pipes can tolerate a wide range of flow changes without the need to change pipe diameter.

The relation between pipe diameter D (mm) and total construction costs per unit length C (USD/m) is described by Equation (7), which is based on Table 5 and Figure 6.

$$C = 0.2609D + 21.15 \tag{7}$$

The results show that reducing supply duration from 24 to 22 hours per day does affect the main design parameter, which is pipe diameter (Figure 7). Reducing the supply duration from 24 to 12 hours per day has a minor impact. Major impacts occur when the supply duration is reduced to less than 12 hours per day: the required pipe diameters increase drastically. Accordingly, reduced supply duration has a substantial impact on the hydraulic gradient (m/km) (Figure 8) and energy costs due to increased hydraulic losses (Figure 9). Reducing supply duration under intermittent-supply conditions implies increasing the flow in the pipes, which increases hydraulic losses, because the pipes' diameters are fixed. Figure 9 shows that in a water distribution system for a locality of 25,000 inhabitants, the energy losses increase from about USD2 m^{-1} y^{-1}, to about USD10 m^{-1} y^{-1}, to about USD30 m^{-1} y^{-1}, as the supply duration is reduced from 24 to 12 and 6 hours, respectively. The impacts of reduced supply duration are more severe on large water systems than on small ones. An example of large supply systems is the water treatment plants in Hyderabad, India, which are capable of providing water for only two hours per day (Mohanty, Ford, Harrington, & Lakshmipathy, 2003).

In the West Bank, many of the existing distribution networks are affected, because the frequency of water supply does not exceed 10 hours per day. Choosing lower pipe diameters to reduce the construction costs of water supply projects exacerbates water-shortage problems and increases the energy bills of the water supply systems. This is another negative impact of the present intermittent water supply regimes. There is a trade-off between the capital costs associated with proper sizing of pipeline diameter and the operational costs due to energy losses in the water supply systems. The Palestinian policy makers and aid agencies are advised to recognize the trade-offs between reduced capital costs and increased operational costs of the water supply systems under implementation.

Linkages with water policy

The Palestinian Water Authority (PWA) has prepared the main principles for national water policy, which was set up in 1996, naming the PWA as a regulator for the national water sector. The water policy was adopted by all legislative, regulatory and administrative bodies (PCBS, 2012; PWA, 2012). Palestinian water policy and strategy focus on the basic water needs of the different sectors, but do not pay sufficient attention to reliability of service, intermittent supply conditions, and the frequency of water supply. Besides, the PWA's specific guidelines for the design of water supply projects are based on continuous-supply criteria and do not recognize the prevailing conditions as well as the potential consequences of such design practices (PWA, 2003). Recently, the PWA has started a reform programme and drafted a new strategy for the water sector (PWA, 2013).

Table 5. Typical construction costs for steel pipelines in the West Bank. All costs in USD/m.

Pipe diameter (mm)	Supply of pipes[a]	Excavation	Laying and testing	Bedding and backfilling	Reinstatement and cleaning	Staffing and overhead	Fitting	Valves and appurte-nances	Contractors' profit	Total
50	13.0	2.5	1.5	2.0	2.5	2.2	1.2	2.5	2.7	30.1
75	19.0	5.0	2.5	3.0	3.0	3.3	1.8	3.8	4.1	45.5
100	22.0	5.0	3.0	3.0	3.0	3.6	2.0	4.2	4.6	50.4
150	24.0	6.0	3.5	4.0	4.0	4.2	2.3	4.8	5.3	58.1
200	28.0	8.0	5.0	5.0	5.0	5.1	2.8	5.9	6.5	71.3
250	35.0	9.0	6.0	6.0	6.5	6.3	3.4	7.2	7.9	87.3
300	40.0	9.0	7.0	7.0	7.0	7.0	3.9	8.1	8.9	97.9
350	44.0	10.0	9.0	8.0	8.0	7.9	4.3	9.1	10	110.3
400	50.0	11.0	10.0	11.0	10.0	9.2	5.1	10.6	11.7	128.6

[a] Concrete-lined and PE-coated steel pipes. Costs collected and compiled by the authors from different sources, mainly from municipalities, NGOs and contractors.

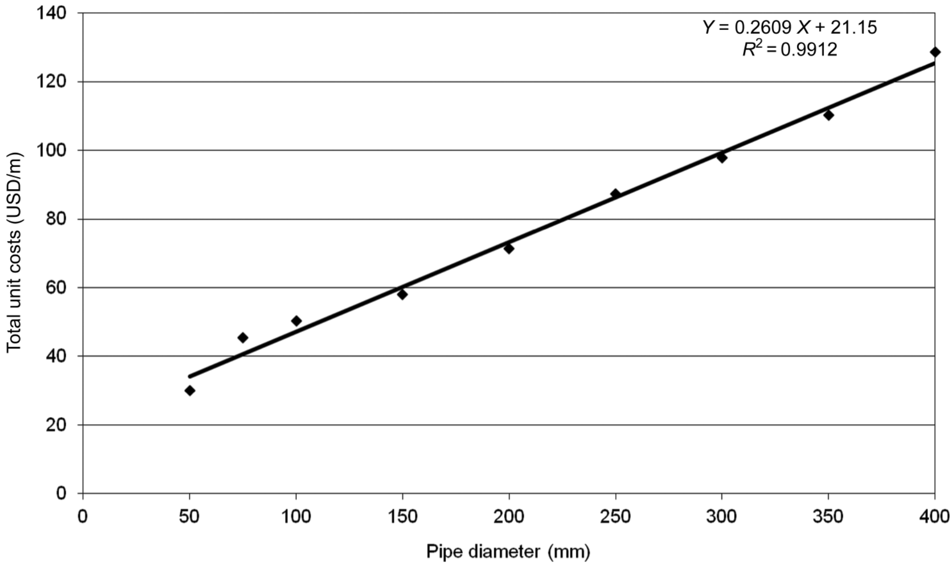

Figure 6. Total construction costs of steel pipes in the West Bank.

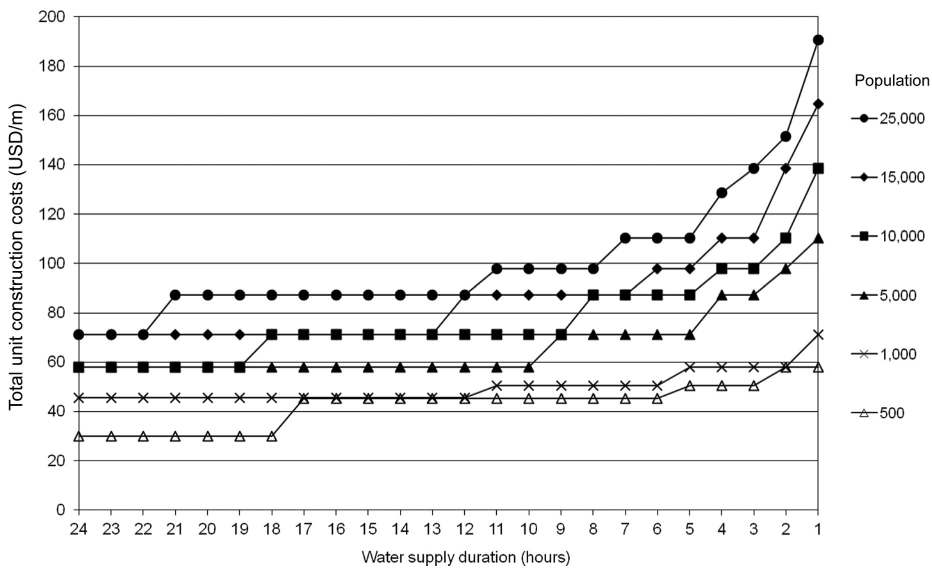

Figure 7. Water supply duration and total unit construction costs of steel pipes.

The results discussed earlier in this paper demonstrate that reducing the supply duration has a severe negative impact on the hydraulics and costs of water distribution projects. Besides, water distribution systems designed for intermittent supply are more expensive than those for continuous supply. The existing policies overlook the trade-offs that exist between the capital and operational costs of water projects and do not provide solutions to the prevailing conditions of intermittent water supply, political dispute and poor economy. Palestinian water policies and strategies are still very weak in terms of enforcement of regulations due to the sovereignty issue over land and water (Nofal, Rabi, & Dudeen, 2007).

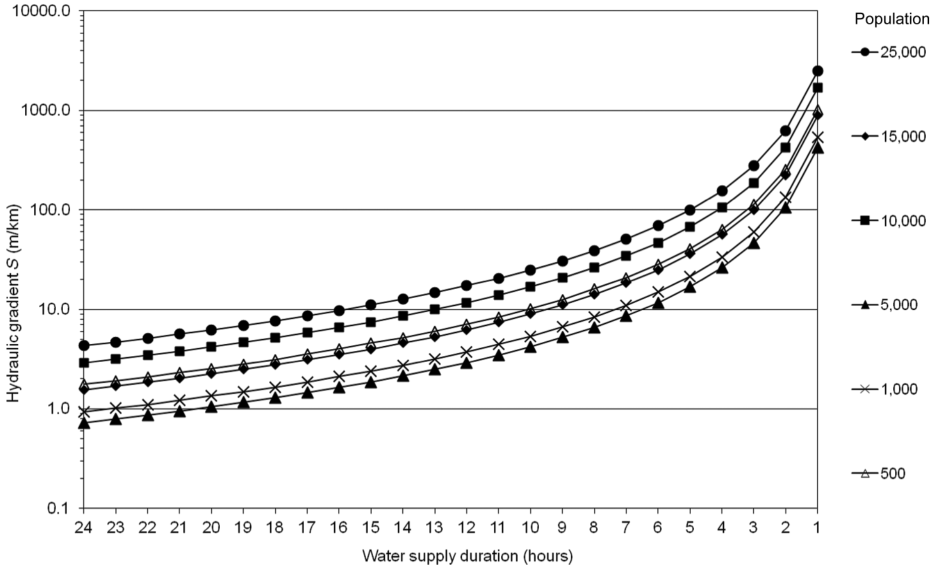

Figure 8. Hydraulic gradient in pipes designed for continuous supply and operated with intermittent supply.

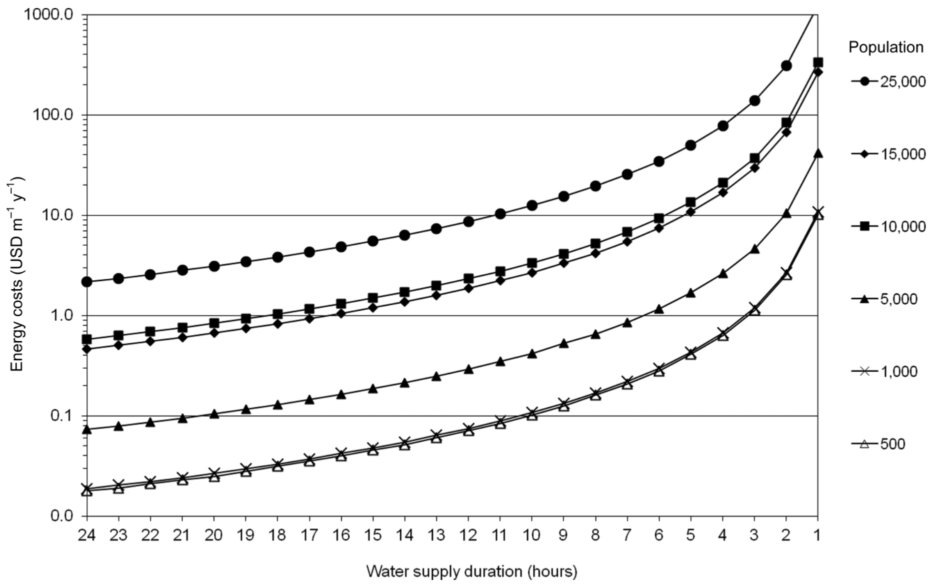

Figure 9. Annual energy costs for pipes designed for continuous supply and operated with intermittent supply.

To switch from intermittent to continuous water supplies, it must be accepted that governance, tariffs and diplomacy are major pillars of any water policy reform (Leshy, 2009; Christian-Smith, Gleick, & Cooley, 2011; Neuman, 2010). To improve water availability, reliability of service and sustainability of the water supply systems, the PWA and other concerned institutions need to adopt effective policies that avoid reducing supply duration. Those policies are of technical, economic and political nature. According to the authors, these techno-economic policies include: (1) adoption of proper design criteria; (2) increasing the diameters of the main transmission pipes; (3) increasing the storage capacity of the public tanks; (4) reducing unaccounted-for water; (5) increasing water tariffs; and (6) raising adequate funding. Such options entail securing additional funds for the investment costs associated with the installation of larger pipes, fittings, storage tanks, and leak detection and repair. Furthermore, it is necessary to adopt effective policies that enforce full cost recovery and build an enabling environment for better involvement of the private sector. Currently, the role of the private sector in the Palestinian water sector is limited to construction contracts.

To improve water availability and make continuous water supplies possible, the Palestinian water quota from the groundwater aquifers needs to be increased. This can be achieved only though water diplomacy, overcoming the existing political complexity between the Palestinians and the Israelis. This calls for revision of existing agreements as well as the tools and mechanisms for negotiations with Israel.

Water pricing, saving techniques and strategies must be integral parts of the water-reform programme and the waste-sector strategy. The existing tariffs are low, and certain categories of consumers in the Palestinian Territory – mainly those in refugee camps – do not pay for water. Accurate water meters must be installed at all consumers' premises, regardless of the geographical, social and political status of those consumers. Higher tariffs need to be imposed, especially when continuous water supply is achieved. Increasing water tariffs often leads to less water consumption and improves water availability. Recently, a prepaid water-metering system was approved by the PWA, and water meters have been installed in a number of villages in the north of the West Bank.

It is necessary to embark on extensive awareness programmes to convince consumers that continuous supply and water availability are possible, at a price. This requires participatory approaches that involve civil-society organizations, including political parties. This will improve public perception of increased tariffs and contribute to water saving. The roles and responsibilities in the water sector are shared by the Joint Water Committee (between Palestinians and Israelis), the PWA, the West Bank Water Department, owners of groundwater wells, private vendors, service providers such as the Jerusalem Water Undertaking, municipalities, village councils, and joint service councils (Selby, 2013).

Embarking on national programmes for reducing non-revenue water will improve water availability and accelerate the switching from intermittent to continuous water supply. This needs to include modern leak-detection facilities, repair of leakages, replacement of old pipes, and tracking of illegal connections. Meanwhile, the design of distribution systems needs to be hydraulically improved; proper criteria must be adopted. Investing in large public storage facilities will mitigate the negative effects of intermittent water supply. Water planners need to consider intra-country transfer of water from water-rich governorates such as Qalqilya and Tulkarm to water-poor governorates such as Jenin and Hebron. This might imply reducing water availability to the agricultural sector, which is a sensitive and political issue. However, stimulating the use of nonconventional water resources, such as treated wastewater, for agricultural irrigation, industry and non-potable uses will secure additional water and minimize the stress associated with any reallocation of water.

Conclusions and recommendations

Reduced supply duration has severe negative impacts on the hydraulics and costs of water distribution systems. Reducing the supply duration to less than 12 hours per day significantly increases hydraulic losses and energy costs. Maintaining the supply duration at more than 12 hours per day reduces the chances of hydraulic failure in the water distribution networks. The water supply duration in many towns and villages in the West Bank is as little as a few hours per week. In this case, designing water distribution systems based on intermittent-supply criteria implies a significant increase in the required pipe diameters, which is costly and infeasible. Water distribution systems in large localities are more sensitive to reductions in water supply duration than those in small towns and villages. Similarly, intermittent-supply conditions have more impact on the main transmission pipes than on the distribution network; i.e. the impacts of reduced supply duration increase with proximity to the water source and decrease with proximity to the consumer.

Reducing the supply duration leads to insufficient water availability for consumers and causes unreliability of the existing distribution systems. These challenges will be exacerbated if the current design practices overlook this fact and assume water availability and appropriateness to provide continuous water supplies. Studying the local conditions of water availability before embarking on the design of new water supply systems is a necessary step in order to avoid reduced supply duration and the resulting negative impacts.

Palestinian designers and project managers often choose lower pipe diameters to reduce the construction costs of water supply projects due to limited financial resources. Such a design practice exacerbates water-shortage problems and increases the energy bills of the water supply systems. This is another negative impact of the present intermittent water supply regimes. There is a trade-off between the capital costs associated with proper sizing of pipeline diameter and the operational costs due to energy losses in the water supply systems.

Most water supply projects in the West Bank suffer from increased operational costs and limited revenues. Increasing water tariffs does not seem to be under consideration due to political complexity and poor economy of the country. Failing to recover the operational costs of water supply systems will add to the financial deficiency of those systems and might jeopardize their sustainability. Palestinian policy makers and aid agencies are advised to recognize the trade-offs between reduced capital costs and increased operational costs of the water supply systems under implementation.

There is an urgent need for water policy reform that considers switching from intermittent water supply to continuous supply; governance, tariffs and diplomacy are the major pillars of this reform. The following guidelines should be at the core of any water policy reform to make continuous supply in the Palestinian Territory possible: (1) improving the criteria for design of water distribution systems and investing in large public storage faculties; (2) improving water diplomacy to overcome the existing political complexity with Israel and increase the Palestinian water quota from the groundwater aquifers; (3) building an enabling environment for private-sector involvement in the water-supply sector, which requires revised regulations and tariffs; (4) imposing higher tariffs, especially when continuous water supply is achieved; (5) reducing non-revenue water; (6) embarking on extensive participatory awareness programmes to convince consumers that continuous supply and water availability are possible, at a price; (7) transferring water from water-rich governorates to water-poor ones; and (8) using nonconventional water resources.

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