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Reframing resilience-oriented urban water management: learning from social–ecological–technological system interactions and uncertainties in a water-scarce city

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Abstract

Non-technical summary. New approaches to ensure the resilience of urban water supply are urgently needed. This requires moving beyond managing water scarcity through infrastructural measures to understanding resilience as an outcome of complex interactions between people, water resources, and technological infrastructure. We conducted expert interviews and a household survey in a water scarcity 'hotspot' and found that water experts emphasize water system deficits and inefficiencies, while citizens complement public water service deficits through (unaccounted-for) coping mechanisms. This leads to uncertainties regarding the outcomes of management interventions. We suggest that integrating different stakeholder perspectives into water management strategies could enhance urban water resilience.

Technical summary. There is limited understanding of how to address the complex dynamics shaping the resilience of increasingly water-scarce cities, globally. By conceptualizing urban water systems as social–ecological–technological systems (SETS) and analysing their interactions from different stakeholder perspectives, we create a pluralistic, yet systematic, understanding of SETS interactions. We conducted expert interviews ($N = 19$) and a household survey ($N = 300$) in Amman, one of the world's water scarcity hotspots, and analysed the data in three steps: (1) We analysed the SETS through the lens of its different actor groups, and, inspired by frame analysis, interpreted each group's system perspective – local experts focus on *deficits* of SETS *elements* and aim to increase available resources, while international experts emphasize the *efficiency* of SETS *interactions.* Households *cope* with deficient water supplies by mobilizing adaptive strategies. (2) Combining these three perspectives, we derived uncertainties resulting from different (and unrecognized) stakeholder views, missing knowledge, and unpredictable system dynamics. (3) We identified and characterized new SETS interactions for an urban, resource-constrained environment, which contributes to a typology aiming for better comparability across SETS. Our results have implications for resilience-oriented urban water management and governance in terms of what to manage (fast/slow variables, connectivity), how (learning/experimenting), and by whom (broad participation).

Social media summary. Addressing uncertainty by reframing resilience-oriented urban water management with complementary system perceptions.

1. Introduction

More than 30% of the global urban population currently live in areas with seasonal or perennial water scarcity, with an expected increase to around 50% by 2050 (He et al., 2021). Hotspots of socio-ecological vulnerability emerge where freshwater stress, storage loss, and limited adaptive capacity co-occur (Huggins et al., 2022). Coincidentally, supply-side management strategies, which rely on water availability imported from increasingly distant locations (McDonald et al., 2014), are reaching their limitations, as demonstrated by 'Day Zero' scenarios from Cape Town to Chennai, from Rome to Mexico City, and from Melbourne to São Pãolo (Dhillon, 2019; Ferguson et al., 2013; Horowitz, 2017; Maxmen, 2018; Millington, 2018).

While research has demonstrated the importance of accounting for water managers' perspectives in urban water management decisions (Burnham, Ma, Endter-Wada, et al., 2016;

Coppock & Brown, 2007; O'Connor et al., 2005), increasing evidence suggests that considering water users' practices and perceptions is critical for addressing water crises (e.g., Savelli et al., 2021; Bettini et al., 2013; Obringer et al., 2022). In Melbourne, for example, citizens' engagement eventually led to more water-sensitive solutions for managing floods and droughts (Ferguson et al., 2013), while public opposition to the consequences of water service privatization in many cities, including Paris (France) and Cochabamba (Bolivia), forced urban managers to return these services into public ownership (Bakker, 2010). Thus, considering both urban water manager perspectives and the concerns of households about the reliability, safety, and affordability of water services (Canter et al., 1992; de França Doria, 2010; Huberts et al., 2023) can promote shared understandings and enable finding the right leverages to maintain urban water resilience (Pahl-Wostl, 2009). However, despite empirical studies highlighting this dual need, conceptualisations of urban water systems and management strategies tend to reflect only the perspectives of managers, overlooking the experiences of water users.

Here, we combine an urban water systems approach in a global water hotspot with a qualitative analysis of different stakeholder perceptions, including water managers, international experts, and household water users. Our analysis consists of three steps: First, we conceptualize urban water supply systems as coupled social–ecological–technological systems (SETS) (Branny et al., 2022). The *social* SETS elements include institutions (laws, rules, and norms that organize how systems are managed), public service providers who take management decisions, and users of the services provided through the infrastructure system. The *ecological* elements are the water resources provided by ecosystems and captured by the *technological* elements, which are physical infrastructure such as dams, treatment and desalination facilities, or distribution networks. The presence and performance of each of the elements, including the adaptability of management strategies and the capacity of citizens to adapt, lead to different system outcomes (Krueger, Borchardt, et al., 2019; Krueger, Rao, et al., 2019; Padowski et al., 2016). In this paper, instead of conducting a full analysis of all the SETS elements, we are interested in how the interactions, relationships, and interdependencies between the S–E–T subsystems (Anderies et al., 2019) may determine outcomes for different stakeholder groups.

Second, we qualify the interactions between the system elements based on stakeholder interviews and a household survey in order to identify their views of the SETS. By analysing how the involved stakeholders perceive the SETS, we aim to reveal how different, disconnected problem-solution frames might hamper the adaptability of water management strategies (Hommels, 2005). Conceptually, this interpretative approach adds a new qualitative layer to our SETS conceptualization and an analysis that integrates diverging frames (Schön & Rein, 1994) derived from stakeholder perspectives who are *within* the system (Klein et al., 2024). This allows us to reveal the uncertainties that arise from different stakeholder interpretations of how the system works and what is at stake. In particular, we are interested in stakeholders' perspectives on changes in stressors and demands that test the resilience of the system. Such stressors can gradually degrade resilience unless accommodated by adequate response, including changes to the system itself.

In a third step, we derive uncertainties from a combined analysis of the results from steps one and two. Besides unpredictable system dynamics, we identify uncertainties that result from missing knowledge and diverging stakeholder views (Zandvoort et al., 2019) and that challenge the improvement of urban water system resilience.

Empirically, we focus on the highly vulnerable urban water system of Amman, where we collected data through mixed methods including expert interviews and a household survey. The capital city of Jordan makes an interesting case due to severe water supply challenges that are typical of rapidly growing and water-scarce cities. Affecting around one billion people in urban areas worldwide (Bivins et al., 2017), water demand in these cities is managed by supplying water intermittently, meaning that water only flows through the pipes for a few hours a day or a few days per week (Kumpel & Nelson, 2016). The resulting 'hammer effect' sends a pressured airwave through the pipes each time the water is switched on, leading to rapid degradation of pipes and increased leakage losses (Simukonda et al., 2018). However, urgently needed repairs and maintenance are often lagging, as scarce financial and labour resources are also needed for expanding water pipe networks into new neighbourhoods. This results in a self-reinforcing feedback loop where water demand is managed through intermittence, which leads to leakage, and leakage losses increase water scarcity. In addition, contaminated water can enter through the leaks, aggravating the water scarcity situation.

Our analysis is guided by three questions:

(1) What are the characteristics of SETS interactions in an urban water supply system marked by scarcity and intermittence?

(2) How is uncertainty about water management challenges intensified through group-specific problem–solution frames?

(3) What are the implications of our findings for resilience-oriented water management?

We address the important, policy-relevant question about whose perspectives shape conceptualisations of urban water systems and thus govern resilience strategies that are developed on the basis of research that accounts for (limited) stakeholder perspectives. We argue that highlighting differences in SETS perceptions and the range of possible interpretations of feedback loops and interactions between SETS elements will produce a more adequate understanding of local dynamics and uncertainties in water-scarce cities like Amman. Our analysis provides insights that can also be relevant for other cities faced with similar pressures of water scarcity and rapid urban growth (Rodina et al., 2024). It is located in one of 168 global 'hotspot' river basins, in which socio-ecological vulnerability is high due to a co-occurrence of freshwater stress, storage loss, and limited adaptive capacity (Huggins et al., 2022). For many decades, Amman has also been a migration hotspot for millions of people seeking refuge from conflict and war in neighbouring countries. Similar to the majority of major cities in the Global South, migration is part of a normal reality rather than an exceptional state. This challenges urban governance to embrace migration as an integral part of the city's development and its potentially transformative role in shaping future pathways (Fry et al., 2024).

2. Conceptual framework

Conceptually, we draw on and contribute to an existing framework and typology of water systems, which we adapt and refer to as the SETS framework. The framework was introduced by Anderies et al. (2019), who referred to it as the 'Coupled Infrastructure Systems framework,' which was built on earlier work by Anderies et al. (2004) and Anderies (2015). As shown in Figure 1, this framework captures the internal complexity of urban water systems, which is increased by exogenous factors that affect system dynamics.

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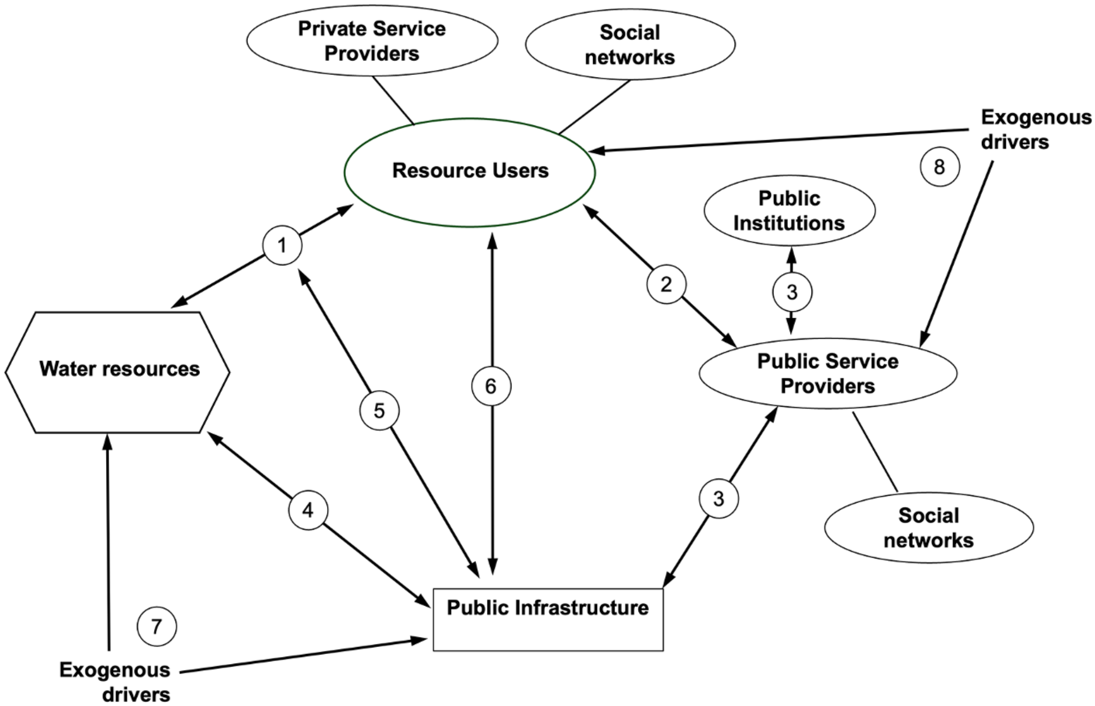

Figure 1. SETS framework adapted from Anderies et al. (2019). Oval shapes refer to 'social' elements of the SETS, diamond shapes to the 'ecological' elements, and rectangles to the 'technological' elements. Numbered links represent interactions relating to those in Figures 2–5 for which they are described in detail in Table 1.

The SETS elements include 'public service providers' representing the actors involved in the city's water management; 'resource users' representing the urban households, including their storage tanks, water filters, pumps, and other water infrastructure installed in private homes; 'public infrastructure' referring to the physical, piped water infrastructure; 'public institutions' being the policies and rules regulating system operation; 'water resources' for urban consumption; and 'social networks' referring to the web of relationships among agents that allow the exchange of resources and information, which can be mobilized by resource users and public service providers (see Results section for further explanation). Resource users can also mobilize 'private service providers', including tanker trucks and water stores (shops). Links between these elements represent perceived material, energy, and information transfers between elements, i.e., SETS interactions. We qualitatively describe these interactions using action verbs (cf. Anderies et al., 2019).

The SETS elements are affected by exogenous drivers and pressures, which include natural hazards such as droughts, economic shocks, or population growth. These exogenous drivers and pressures constantly test the resilience of SETS. Resilience refers to the ability to buffer, persevere, respond, and reorganize in response to shocks and disturbances (Gunderson & Holling, 2002; Krueger et al., 2022; Levin, 1999). Resilience requires preparedness and adaptive capacity and is enhanced by creating redundancies in the supply network, diversity of sources, modularity to reduce losses and isolate contamination events, and the capacity to respond to disturbances through tight feedback loops (Levin, 2019; Levin & Lubchenco, 2008). When a current system becomes untenable, maintaining resilience requires a system to transition into a new regime with different feedback mechanisms that may require different management and governance approaches (Biggs et al., 2012; Folke et al., 2021). Learning and flexibility are key to resilience, both in its adaptive and its transformative phases (Pahl-Wostl, 2009; Park et al., 2011).

Following Zandvoort et al. (2019), we identify three different types of uncertainty that call for different systemic responses. First, uncertainty about how the system might change due to variability and non-linear behaviour in different system elements (*ontic* uncertainty). The resulting uncertainty produces an unpredictable future and is irreducible within the system; it can only be accommodated by strengthening general system resilience. Second, missing knowledge (*epistemic* uncertainty) can be addressed by collecting more information about the system. Third, *frame* uncertainty results from different stakeholder perspectives (Zandvoort et al., 2019) and calls for increased communication, exchange, and mediation. The idea of diverging frames is based on the assumption that distinct groups of stakeholders develop shared understandings of problems and suitable solutions, including who or what is to be held responsible and what actions should be taken (Benford & Snow, 2000).

3. Methods

This research was developed and conducted based on several extended visits to Amman by the first author, who designed the study and collected and analysed the data. During her field research, she observed water-related processes in Amman and had in-depth conversations with local experts, aiming to understand how knowledge is generated and information is shared about water resilience issues. The third author has decades of experience living in and working on water-related issues in Amman, and the second and last authors have extensive experience in studying and interpreting different stakeholder perspectives. All authors have worked on issues related to water management and SETS in various contexts and discussed their different perspectives with each other to reflect their own blind spots and biases and also in reflection of the local and international experts' perspectives. Interviewees were used to the presence of and interaction with international researchers, as national and international researcher groups have been very active in studying the water sector in Jordan for many years.

As the data were collected in 2015 (expert interviews) and 2016 (survey), our case study description focuses on that period to match the perspectives of the participants, and we point out any significant developments since the study period. Data collection was approved by Purdue University's Institutional Review Board (#1604017599).

3.1. Case study

Jordan is one of the most water-scarce countries in the world, and at the time of this research, its capital city, Amman, had a low water availability of 121 litres per capita and day. Severe water scarcity challenges are expected within the coming decades (Yoon et al. 2021). Amman receives its water from nearby groundwater wells and springs (about 25% in 2015, down to 20% in 2022), mixed surface and desalinated water (~30% in 2015, 44% in 2022), and non-renewable groundwater (45% in 2015, 36% in 2022) from the Disi aquifer near the country's southern border with Saudi Arabia. Local groundwater wells are over-exploited and supply from the fossil Disi water is expected to terminate within the coming years. Amman's population has increased from around half a million in the 1960s to over four million in 2015. This rapid population growth has largely been driven by the repeated influx of refugees fleeing from conflicts and wars in neighbouring countries (UNHCR, 2016). To supply up to 40,000 (6%) additional customers every year (Miyahuna, 2014), infrastructure is expanding rapidly and additional resources are accessed at increasing distances. To meet growing demand, the most significant anticipated water infrastructure project aims to desalinate and import seawater from the Red Sea (MOPIC, 2022; Lindsey, 2023; Rabadi, 2016).

Amman's water supply infrastructure is technologically sophisticated and financially expensive: Water transfers reach distances of up to 350 km, overcome altitude differences of over 1000 m by pumping, and low raw water quality requires treatment and mixing before distribution to customers. Ninety-eight per cent of Amman's households are connected to piped water supply. Due to the scarcity, urban residents received water intermittently for 2.5 days per week on average in 2015 (down to 24 hours per week in 2024). Intermittent supply causes strongly fluctuating high and low pressures and triggers pipe bursts and leakages. A large fraction of piped water is lost as 'non-revenue water' (NRW), which includes water lost through leaking pipes and 'administrative losses,' i.e., unmetered or otherwise unaccounted-for water. In 2013, NRW was around 37% (Ministry of Water and Irrigation, 2013). Eighty per cent of the population was connected to the sanitary sewer infrastructure, prone to blockages and repairs (Miyahuna, 2014). Amman's residents, whose wealth and income are highly unequal (Potter et al., 2010; UN, 2011), are charged a fixed fee for their piped water and a consumption-based rate according to a tiered tariff system. To bridge supply gaps and increase water availability, some households buy additional water delivered by private tanker trucks or in canisters from specialized water stores. Bottled drinking water is also common.

Several levels of governance characterize Amman's water system: Decisions are taken at the national and ministerial levels, while two national water authorities share responsibilities regarding water allocation and investment (Jordan Valley Authority is responsible for agricultural water supply and monitors dams and reservoirs and bulk water allocation; Water Authority of Jordan is responsible for water resources planning, urban supply, and wastewater affairs). The urban water utility (a government-owned company) operates and maintains the water supply and sanitation networks and collects water revenues. According to the Central Bank of Jordan, government debt was 93% of GDP in 2015 and, being a public company, the water utility operates under a chronic budget deficit (Miyahuna, 2014). International donors are critical in providing financial investment capital for the water infrastructure (Miyahuna, 2014), but investments are insufficient for maintaining and expanding water infrastructure. International water experts are strongly involved in the development of Amman's water sector. However, Bonn (2013) points out that, despite their critical role, donor organizations are largely acting in isolation from local actors as their views on water resource realities and management approaches diverge from those of Jordanian governmental bodies.

These problems persist. The drought that Jordan has been facing since 2019, combined with growing demand due to, among others, ongoing conflicts in neighbouring countries, has led to aggravating water scarcity in recent years, with water availability reduced by up to 30%, depending on the season. Initial uncertainty and then downsizing of the planned Red Sea water desalination project, as well as continued NRW problems (around 40% in 2023), have sparked renewed interest in understanding what is needed for thinking about the resilience and sustainability of this system.

3.2. Data collection

Expert interviews ($N = 19$) were conducted by the first author in May/June 2015, which included 14 local and 5 international representatives with expertise in Amman's water decision-making and management. They were selected using a purposive sampling technique (Creswell & Clark, 2018) based on prior literature research, and in consultation with our main local contact at the water ministry during preparatory visits. We contacted additional persons recommended by the interviewees (snowball sampling; Neuman, 2011). All interviews took place in face-to-face, in-person meetings with the first author and were conducted in English. Interview questions were semi-structured and focused on the interviewees' interactions with/in the SETS, particularly (1) information sharing, feedback loops, and communication pathways among actors in the water sector and across sectoral boundaries, (2) decision-making, operational procedures, and bottlenecks in the implementation of water-related projects, and (3) challenges to the long-term, reliable urban water supply, as well as potential pathways to addressing these challenges. To contextualize the interview responses, we asked the interviewees to reflect on water-related projects and processes that we co-identified with our local partners and that were topical and important in Amman at the time. These included the allocation of resources among urban and non-urban users after the implementation of a major water transfer project, a major water investment project in the water distribution system within the urban boundaries, as well as interactions with urban water users for meeting daily demands. The interview guide can be found in the Supplementary Information (SI).

To elicit water users' perceptions of the water system, we conducted a face-to-face household survey ($N = 300$) in July/August 2016. The questionnaire was developed by the first and second authors based on a literature review and field observations, notably

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insights shared by our local partners, informal conversations with the local population, and key themes that emerged from the expert interviews. To include household samples from across the heterogeneous socio-technological characteristics of the city, we selected a cross-section of neighbourhoods from north to south and from east to west. Along this cross-section, we sampled neighbourhoods representing high- and low-income households, different supply durations (according to the utility's rationing schedule), and different infrastructure reliability (based on the frequency of reported pipe bursts provided by the water utility). Furthermore, surveyors were asked to spatially distribute respondent households within the selected neighbourhoods by limiting participants to one per building and two per street, while balancing between feasibility and geographical spread. The questionnaire was developed in English and translated to Arabic, piloted with 20 local respondents, and implemented through door-to-door in-person interviews by a local, mixed-gender team of 10 trained surveyors (recent university graduates). The questionnaire had six sections containing open-ended and closed questions to elicit perceptions of challenges and adaptive responses regarding (1) water supply reliability, (2) water quality, (3) adaptation to water service deficits, (4) challenges to the long-term, reliable urban water supply and potential solutions to these challenges, (5) the respondent's contacts and interactions with others around water-related issues ('water-ego-nets'), and (6) demographics.

Finally, to better understand potentially diverging problem–solution frames, both expert interviewees and household survey respondents were asked to rate Amman's water resilience based on a list of 16 items and two questions about potential solutions. The survey questionnaire can be found in the SI.

As our data collection allowed us to only take a single snapshot in time, we asked both household respondents and expert interviewees about observed changes to the system to account for and understand dynamics from recent changes to the system (∼5 past years), such as the recent influx of Syrian refugees, and a new water source that reached the city around the same time.

3.3. Data analysis

All data were analysed separately for stakeholder interviews and households, and followed a three-step procedure.

First, we recorded the interview results and open-ended survey questions as text organized around the key SETS elements based on them being mentioned during the interviews. To answer research question 1 (RQ1), we followed Anderies et al. (2019) by identifying processes in the recorded interview and survey data and coded them as SETS interactions. Thus, we substantiated and characterized specific interaction links using action verbs and based on how the stakeholder groups described the processes and activities taking place between the SETS elements. For household respondents, we relied on detailed survey questions on their interactions within the SETS and their household-level coping strategies (survey section B Adaptation). While the SETS approach does not allow for unpacking feedback mechanisms within the elements of the SETS, such as power structures and specific interactions among actors within stakeholder groups, it is useful for characterizing interactions between SETS elements, which is the focus here. While completing the SETS typology of link characteristics (Table 1), it became obvious that the stakeholder groups characterized interactions differently, and some interaction links were missing from their responses.

In the second step, we therefore further explored whether we could identify group-specific patterns in the stakeholder responses based on a frame analysis (Schön & Rein, 1994). In particular, we focused on group-specific patterns in the interviewees' and survey respondents' descriptions of water-related problems and possible solutions (RQ2, part one). While the interviews offered rich information on how local experts and international experts framed the Amman situation, households' problem–solution frames were sketched out based on an open question on desirable improvements of their water situation, combined with survey responses on water supply reliability (survey section A), water quality (section C), and long-term issues (section D). The overlaps among responses within the three identified stakeholder groups give us confidence that our data offer a sufficient level of saturation and that the sample size was adequate for the purpose of this article (Hennink et al., 2017).

In step three, we combined our results of the three stakeholder groups in an integrated assessment of SETS interactions in order to identify and characterize uncertainties (RQ2, part two). We integrate our insights and relate them to what we know about improved water service resilience in the discussion (RQ3).

4. Results

4.1. Local expert perceptions

Interviews with local experts provided the most comprehensive account of SETS interactions (Figure 2; compare Figures 3 and 4). Local experts mentioned the need to 'negotiate laws, rules and water tariffs' (Figure 2, Link 3c between Public Institutions and Public Service Providers). In particular, they spoke about aligning legal frameworks for the water sector and the need to increase water revenues through raising the water tariff and government funding. Furthermore, they mentioned that infrastructure maintenance was falling short over the need for emergency response due to frequent pipe bursts and a shortage of repair teams, and the need to expand the sanitary infrastructure. We marked this as a limitation to 'invest in, maintain, and manage infrastructure' (Link 3a). Repairs were complicated by imprecise infrastructure data, indicating that data to 'inform management decisions' (Link 3b) was lacking.

Local experts also described how the recently installed (Disi Aquifer) and planned water-import infrastructure (Red Sea water to be desalinated and transported to the city) 'modify, control water allocations and landscapes' (Link 4a between Public Infrastructure and Water Resources). They discussed leakage losses caused by intermittent supply and frequent pipe bursts, which 'damage, erode water infrastructure' (Link 4b). They recognized the lack of adequate ('smart') water metering to better estimate sources of NRW (missing Link 5b) and mentioned that (some) households *used* water 'wastefully' (Link 1a), justifying the need for rationing and *restricting* water supply (Link 5a).

Regarding the interactions between Public Infrastructure and Resource Users, local experts mentioned a high demand for new water service connections (Link 2a), which 'enable water extractions' (Link 6a). An 'increase in population' due to immigration from neighbouring countries was perceived to cause rising water demand (Link 8a, Exogenous driver). They further discussed the closing of illegal groundwater wells (where water is often sold to private tanker trucks) and the licensing of private tanker trucks ('Private Service Providers', Link 6c). While it was obvious to them that the private tanker market complements public water services

Table 1. SETS links characterizing the interactions between the elements of Amman's water supply system

Link	**From → to**	Action verb with potential impact on receiving element (±/∼)	SH	Notes on stakeholder perceptions
1a	Users → WR	− *use*	LE	Potential for profligate use by HH
			HH	Equipment, time, and financial effort
1b	WR → Users	+ *flow* (water quantity, quality)	HH	See 5a, mostly sufficient quantity
2a	Users → PSP	+ *pay* water bills	IE	Only link
			HH	Too costly for some
		∼ *complain* about service disruptions	IE	System in place
			HH	System in place
		∼ *demand* water service connection	LE	High demand
2b	PSP → Users	± *inform*	IE	Lacking
3a	PSP → Infrastructure	+ *invest* in, + *maintain*, ∼ *manage* infrastructure	LE	Funding and maintenance deficit
			IE	Constrained 'piecemeal' investment, planning/funding deficit
			HH	Insufficient response to complaints
3b	Infrastructure → PSP	+ *inform* management decisions	LE	Data deficit
			IE	Data deficit
3c	PSP → Institutions	∼ *negotiate* laws, rules, water tariffs	LE	Need for alignment, revenue deficit
			IE	Missing protocols, inefficiency
3d	Institutions → PSP	± *coordinate* management	LE	Constrained by siloing
			IE	Lacking, 'top-down' decisions
		∼ *govern* management processes	IE	Resistance
4a	Infrastructure → WR	− *extract*, ∼ *control* water allocations and landscapes	LE	Current resources insufficient
4b	WR → Infrastructure	− *damage*, − *erode* water infrastructure	LE	Pipe bursts, water leakage
			IE	Inefficient construction, technical losses
5a	Infrastructure → Link 1a/b	− *restrict* water extractions through rationing, low water pressure	LE	Demand management
			HH	Delays, low pressure
		− *pollute* water resources due to degraded infrastructure	HH	Quality issues, filtering
5b	Link 1a/b → Infrastructure	∼ *inform* decisions about infrastructure investments based on demand through metering/monitoring	LE	Lack of metering
			IE	Missing decommissioning, inefficient construction
6a	Infrastructure → Users	+ *enable* water extractions (pipe connections), + *deliver* water	LE	High demand
			HH	Exists/lacks, pipe bursts
6b	Users → Infrastructure	∼ *co-manage*	/	Household-level infrastructure as form of (co-)management?
6c	Institutions → PP	− *sanction* illegal abstractions	LE	Closing of illegal wells
		+ *license* private suppliers	LE	Complement supply during deficits
6d/e	Users ↔ Institutions	∼ *co-develop*, − *restrict*/+ *enable*	/	Rules/protocols for water user behaviour/participation in decision-making
7a	Exogenous → Infrastructure	− *restrict* infrastructure development	LE	Deficits in coordination, high prices
			IE	Draining of water sector budget
		− *damage* infrastructure	LE	Construction/maintenance work
7b	Exogenous → WR	+ *access/exploit* new resources	LE	Red Sea transfer
8a	Exogenous → Users	+ *increase* population	LE	High immigration rates, higher water demand

(*Continued*)

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Table 1. (*Continued.*)

Link	**From → to**	Action verb with potential impact on receiving element (±/∼)	SH	Notes on stakeholder perceptions
8b	Exogenous → Institutions	+ *coordinate* regulation across sectors	LE	Constrained by siloing
			IE	Constrained by siloing
		∼ *influence* institutional development	IE	Aid programmes
8c	Exogenous → PSP	+ *fund* infrastructure investment	IE	Dependence, missing prioritization
		∼ *influence* decision-making	IE	Aid/funding
		– *drain* institutional/managerial knowledge	IE	'Brain drain'
9a	PP → Link 1 a/b	+ *enhance* water extractions	HH	Tanker truck delivery
9b	Users → PP	+ *pay* for alternative services	HH	Daily/weekly or during delays
10	PP → WR	∼ *influence* water allocations	/	Over-extracted water from private wells and surface water modifies water allocations
11a	WR → PSP	*inform*	/	Monitor water levels
11b	PSP → WR	∼ *modify, control* water allocations and landscapes	/	Decisions about allocation between sectors and types of infrastructure
12	Social networks → PSP	∼ *influence* PSP agency	IE	Shifting power and responsibility
13	Social networks → Users	+ *strengthen* adaptive capacity	HH	Supporting water service functioning

LE = local experts, IE = international experts, Users = resource users, WR = water resources, PSP = public service providers, Infrastructure = public infrastructure, Institutions = public institutions, PP = private service providers, Exogenous drivers = exogenous. Symbols before the action verbs indicate the potential impact on the receiving element: increase (+), decrease (−), and change (∼), where change can refer to structural changes of the element, or changing the availability of information based on which decisions can be made. SH stands for the stakeholder group that mentioned the link with notes on their perceptions in the last column. '/' in the column 'SH' indicates links suggested by the authors (i.e., not mentioned by stakeholders, see Section 5).

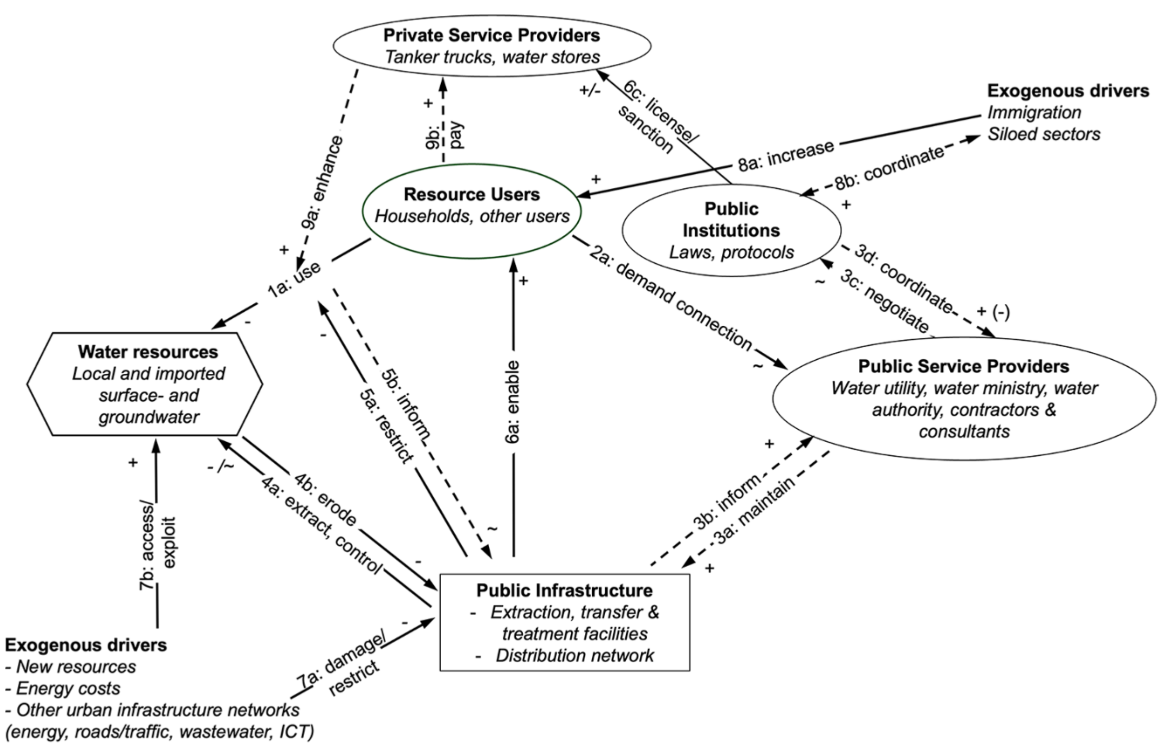

Figure 2. SETS elements and interactions as perceived by the local water experts (Links 1a, 3a–d, 4a,b, 5a,b, 6a, 7a,b, 8a,b, and 9a,b). Dashed lines indicate links perceived as missing, constraining, or uncertain. Symbols indicate the potential impact on the receiving element (+indicates increase, − indicates decrease, and ∼ indicates change, where change can refer to structural changes of the element, or changing the availability of information based on which decisions can be made), which can be constrained by deficits. ± indicates that the receiving element can either be increased/decreased or improved/reduced (e.g., Link 6c 'licensing/sanctioning' can increase/decrease the number of private service providers).

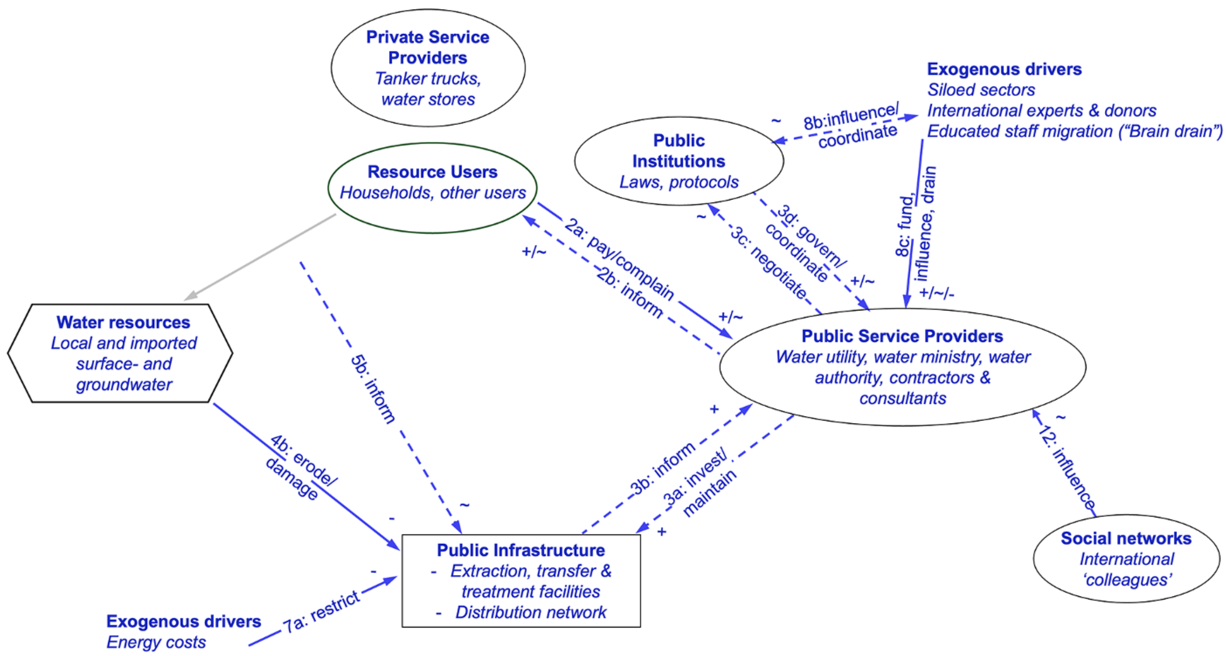

Figure 3. SETS elements and interactions as perceived by the international experts (Links 2a,b, 3a–d, 4b, 5b, 7a, 8b,c, and 12). Dashed lines indicate links perceived as weak or missing. Link from resource users to water resources was not mentioned by international experts, but a lack of metering to monitor water extractions by households was mentioned as missing. We therefore inserted this link in light grey (without label).

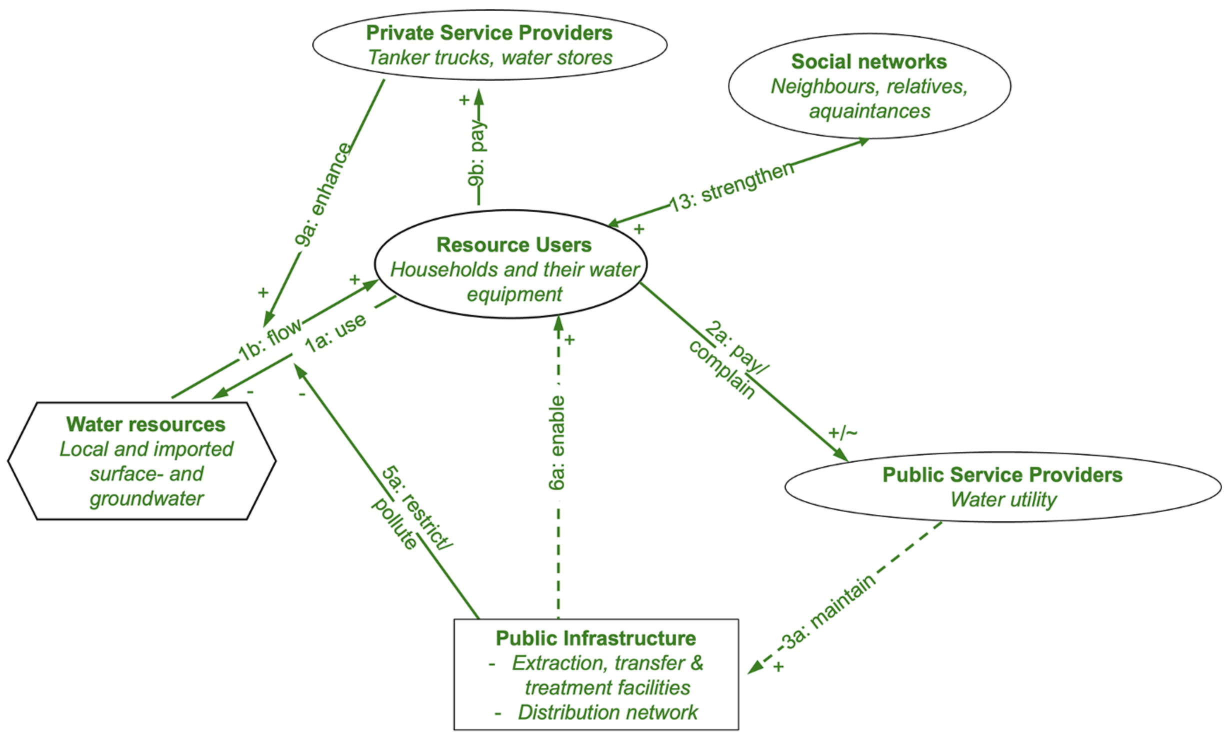

Figure 4. SETS elements and interactions as perceived by households (Links 1a,b, 2a, 3a, 5a, 6a, 9a,b, and 13). Dashed lines indicate links perceived as weak or missing.

to households (Links 9a,b,c), they remained unclear about who benefitted from these services, by how much, and at what cost. We discuss this further in Section 4.5.

Furthermore, local experts mentioned constraints in infrastructure development that resulted from legal, fiscal, and operational silos, which regulated different types of urban infrastructure. They perceived adequate infrastructure planning to be outside of their control, as urban planning was the responsibility of the municipality. Accordingly, they emphasized the need to 'coordinate regulation across sectors' (Link 8b from External driver 'Siloed sectors' to Public Institutions) as this also affected Public Service Providers by constraining 'coordinate(d) management' (Link 3d).

Urban infrastructure networks, such as (waste-)water, energy, Information and communication technology, and roads are often co-located, such that construction or maintenance on one network can cause damage to another. However, each sector was subject to its own specific regulations and protocols for data documentation and storage (Public Institutions), which led to information and data sharing issues. For example, the laying of water pipes was subject to the national water law, while opening up the roads underneath which the pipes are laid was subject to the national road law and the responsibility of a different ministry, or needed to be transferred to the municipality for constructions within the urban boundaries, and required permission to interrupt traffic from the local police department. The involvement of too many entities meant delays for time-critical issues, such as repairing leaking or burst water mains and sewers. The interactions with 'Other urban infrastructure networks' thus also restricted the development of Public Infrastructure (Link 7a). Energy prices were perceived as another constraint to water system development, as around 20% of nationally generated electricity was used in the water sector and electricity costs constituted 52% of the utility's expenditures (Link 7a). The planned desalination and transfer of water from the Red Sea was frequently mentioned as the solution to increasing water scarcity issues ('access new resources', Link 7b): a project reliant on international donor funding.

4.2. International expert perceptions

International experts are part of the Amman SETS; they are an external driver, but also advisors and colleagues with specific ties to individual local experts. In Figure 3, they are added as 'Social networks' of Public Service Providers, but also play a role as 'Exogenous drivers.'

International experts offered a less comprehensive picture of Amman's water SETS (Figure 3). They emphasized the lack of water sector funding resulting in the inability to invest in and to adequately manage infrastructure (Link 3a). They identified the need to adjust water prices to fully recover operation and maintenance costs. Although they considered the structure of water sector institutions to be good and the involved actors to be technically skilled, they perceived a lack of protocols for project prioritization, execution and assessment, and the need for a more holistic approach tying together different investment projects. Thus, we marked 'negotiat(ing) laws, rules, water tariffs' (Link 3c) as lacking. They also observed resistance to reform. Laws considered to be inadequate were not corrected through institutional reform, but instead exceptions were granted suggesting that Public Institutions had limited influence on 'governing management processes' (Link 3d). International experts also perceived decisions to be announced *ad hoc* and communicated 'top-down' from the highest government levels or the utility's directorate, and criticized a lack of coordinated urban and infrastructure planning and management (Link 3d). Deficits in infrastructure mapping and data collection explained a lack of 'inform(ed) management decisions' (Link 3b).

International experts perceived the water sector as vulnerable, because its performance depended on the knowledge and actions of individual actors rather than on strong institutions. This was also reflected in the fact that international donor organization had different connections with different individuals and water management bodies that form part of Public Service Providers (Link 12). These connections effectively determined local responsibilities for investment projects, undermining existing rules for the distribution of responsibilities for water infrastructure development.

International experts found investment and maintenance into infrastructure to be inefficient (Link 3a); rapid urban development and the fast pace of laying pipes into new neighbourhoods left little time for adequate planning. Monitoring water system flows was difficult (Link 5b), as sometimes several pipes laid in parallel. Thus, technical losses and leakage, aggravated by pipes damaged by intermittent water supply (Link 4b), were perceived as the most urgent water infrastructure-related challenge.

When asked about private tanker trucks, international experts seemed to lack detailed knowledge about this informal market. To reflect this, we did not specify any links to Private Service Providers in Figure 3. See Section 4.5 for a further discussion of this topic.

Furthermore, international experts noted that investments into public infrastructure were fully dependent on international donors (Link 8c), whose dominant role also meant that investment prioritization was not based on the most urgent needs, but on the donors' willingness to fund specific projects. This led to perceived piecemeal and isolated interventions rather than systemic problem solutions, which we identified as an indirect influence of Link 8c on Link 3a. International experts perceived energy costs to be draining water sector budgets, 'restrict[ing] infrastructure development' (Link 7a). To address this issue and the reliance on increasingly expensive energy imports, they suggested that the water and energy sectors should be coordinated. Ninety-seven per cent of national energy resources were imported from other countries, and water sector subsidies accounted for 20% of government deficit in 2010 (OECD, 2014). Despite the country's plans to construct a nuclear power plant for generating electricity on national ground (NEI, 2023), coordinated planning and regulation (Link 8b) was perceived as missing (e.g., regarding the need for cooling water). International organizations influenced decision-making (Link 8b) and the institutional development (Link 8c) of the water sector, for example through the Institutional Support and Strengthening Program of the United States Agency for International Development (USAID). One expert mentioned the loss of well-educated staff ('brain drain') as a problem, as jobs abroad were better paid (Link 8c).

Finally, international experts saw little interaction between water management agencies and the general public although the water utility service desk allowed water users to submit complaints and make inquiries about service disruptions (Link 2a). However, the experts perceived a lack of response to complaints (Link 2b). As one interviewee noted: 'The only interaction between customers and [the water utility] is through their water meters.'

4.3. Household responses

Household responses highlighted issues of reliability and quality of their water supply and offered insights on some SETS interactions (Figure 4). Survey participants reported delays in water delivery and issues with water pressure and quality (taste, smell, and health concerns). The vast majority of households either filtered piped water or resorted to store-bought water for drinking. The interaction between water resource and users is described as 'flow' (Link 1b) and the constraints to this flow 'restrict(ing) water extractions through rationing, low water pressure' and 'pollute(d) water resources due to degraded infrastructure' (Link 5a), because water quality issues may result from polluted water intruding distribution pipes during low water pressure. All households reported using private water equipment, including rooftop storage tanks,

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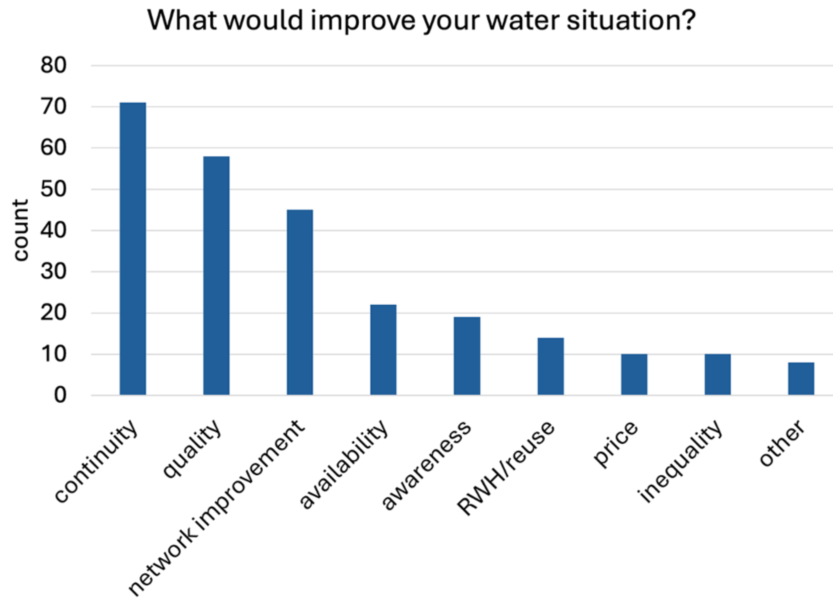

Figure 5. Household responses regarding desired improvements to water service deficits.

most reported using water filters to treat water before drinking, and we know from conversations with water engineers that some households used pumps to increase water pressure to fill their storage tanks. These actions represent efforts invested by households to use water resources (Link 1a) and to adapt to intermittent water supply. About a quarter of surveyed households bought additional water from tanker trucks or water stores on a daily or weekly basis, while the rest only 'paid for private services' (Link 9b) to 'enhance water extractions' (Link 9a) when piped supply was insufficient.

More than half of households reported that they complained to the water utility when experiencing water delivery delays (Link 2a). Yet, they also reported – in line with the international experts' observations – that the utility responded slowly or never to their complaints, e.g., in the form of infrastructure improvements and repairs (Link 3a). Instead, social networks played an important role for household water resilience 'strengthen[ing their] adaptive capacity' (Link 13). In particular, relatives and neighbours supported the functioning of water supply by checking storage tank levels and conditions, calling water tanker trucks, or sharing water among neighbours when storage tanks ran dry (see the SI for details). Forty per cent of households mentioned having experienced pipe burst(s) in their neighbourhood, and one surveyed household was without a pipe connection (Link 6a).

The average daily volume of piped water supplied in the city was 68 litres per capita (compare Europe: 150 litres, the USA: 350 litres). When asked in an open question what would improve their water situation, Link 5a appeared most important: 24% of household respondents wished for continuous water supply, 19% for improved water quality, and 15% for infrastructure network improvements. Only 7% responded that more water availability (Water Resources and Link 1b) and 3% that a lower water price would improve their water situation (Link 2a). Figure 5 summarizes these results (see the SI for more results).

4.4. Complementary and diverging problem and solution frames

In light of the differences between the stakeholder groups' views, we further explored group-specific patterns regarding the problems of Amman's water supply system and potential solutions. We found that local experts were mostly concerned about deficits in the SETS elements: Water Resources, Public Infrastructure, and Public Institutions. They mostly perceived SETS links as instruments to reduce capacity deficits in SETS elements and to control resource users and exogenous drivers, including cross-sector interactions. We interpret this as a 'deficit frame'. Their solution to these deficits is to increase revenues and the capacity of the system by (1) building desalination and transfer infrastructure to access additional water resources, (2) determining and reducing water losses, including the sanctioning of illegal abstractions, and (3) creating an 'umbrella law' to streamline water-related regulations and coordinate across sectors.

In contrast, international experts were more concerned with inefficiencies in Amman's water supply system. They aimed at enhancing the efficiency of public institutions and public service providers. Their description of SETS links reveals an 'efficiency frame', which directs their attention to infrastructure planning and monitoring, construction work, data sharing, knowledge management, and leakage repair. One international expert criticized that Amman's water supply system was based on the principle of 'getting water to the customer' without consideration of how efficiently it gets there. Information sharing, reporting, and feedback protocols were described as weak, particularly across sectors and between government bodies. They observed that information sharing always required prior approval and to be shared only upon request from higher levels of government. As a result, problems often only surfaced as emergencies requiring immediate attention, and obstructed informed and strategic decision-making processes to address the underlying causes. This inefficient communication was explained by a competition for power, financial dependencies, and a lack of trust and accountability between different government levels and sectors.

Comparing the different expert frames, we see that they situate the problem differently: a deficit of the SETS *elements* versus an efficiency problem in SETS *interactions*. More precisely, international experts put greater emphasis on the links between SETS elements, with more action verbs describing missing or weak interaction links, and proposed solutions aiming to enhance the efficiency of flows and interactions. In contrast, local experts put greater emphasis on deficits in the SETS elements as such, with solutions prioritizing the enhancement and strengthening of SETS elements and resources.

Some of these views and proposed solutions seem complementary. For example, infrastructure deficits in the form of frequent pipe bursts and resulting leakage mentioned by local experts (Link 4b) were explained by international experts with inefficient construction, such as pipes not being placed deep enough in the ground. Furthermore, local experts emphasized the incompatibility of existing laws and rules across different authoritative structures and ministries that share responsibility in the water supply sector (Links 3c and 3d). They thought that the strong siloing between sectors, which hampered coordination, would require an external actor to mediate between sectors. Here, international experts found horizontal, cross-sector coordination to be inhibited by the top-down manner of vertical communication following strong hierarchies of governance structures, by missing or inefficient protocols and procedures for information sharing, and noticed a resistance to governance changes.

Other views were more diverging, such as the full-cost recovery model proposed as a measure to recover the financial deficit. This was discussed by both local and international experts, but seemed problematic in terms of user affordability. Those responsible for making that decision acknowledged financial limitations on the households' side and, while promoting the discourse around full-cost recovery, hesitated to implement it. Furthermore, constraining this approach is the aggravating financial and water scarcity situation, as well as large leakage losses through eroding infrastructure, and loss of management capacity ('brain drain' seems to have accelerated in recent years, pers. comm., 2024). Irrespective of acute external pressures and local specificities, international experts insisted on addressing inefficiency. Full-cost recovery under a 'New Public Management' paradigm (Lapuente & Van de Walle, 2020) aligns with this 'efficiency frame'. The international donors, themselves operating under an efficiency paradigm, aim to maximize the efficient use of investments and local potentials. In line with this, international experts prompted the water utility to develop 5-year prospective 'Strategic Business Plans' each year, focusing on management efficiency and strategic, long-term planning. However, we observed that the organizational structures laid out in these reports had little value for understanding how power is structured and how information flows and communication occurs among the various levels of organization and groups of stakeholders in the specific context of Amman. We further observed that water management strategies needed constant adaptation, such that long-term plans quickly became obsolete in the face of repeated waves of refugees fleeing conflicts in neighbouring countries. Thus, the international experts' aim to enhance efficiency seems at odds with specific local challenges like power relations and the frequent and acute external pressures. Despite following donor demands for more transparency and reporting, and the adoption of New Public Management discourse, it remains unclear whether these approaches align with the principles and values of local experts.

The survey results suggest that households were experienced in coping with deficient water supplies and were concerned with improving the outcome that public infrastructure produced for them. This perhaps unsurprising result emphasizes residents' low level of agency in conventional, centralized water supply systems more generally. Although households were asked a different set of mostly closed questions, four main indicators lead us to suggest the households operate within a 'coping frame'. First, our opening question to the household survey asked whether respondents generally experienced water supply problems. Fifty-five per cent of the surveyed households responded 'no, never', despite the fact that these households received water, on average, on 2.5 days per week. We interpret this result as the majority being adapted to the average level of services they received, rather than as an indication of reliable water supply. Similar results were found by Huberts et al. (2023), who reported that most households receiving water intermittently in Mexico City were satisfied with their supply. Second, households reported a variety of coping strategies, including, storage reservoirs, sharing of water among neighbours, support networks to ensure water service functioning, and water treatment at home, while also desiring more reliable water supply. Third, when asked about what would improve their situation (open question, Q26), the most frequent responses were 'continuous water supply' and 'improved water quality' (Figure 5). These issues require major adaptation effort by households: Ensuring that valves are open when the water arrives, tanks are filled, water is used cautiously to make it last until the next delivery, and water is treated to make it safe to drink. Lastly, the design of the survey as a face-to-face interaction allowed respondents to qualify their answers, indicate when questions were non-applicable, or response options were not suited to their situation. This ancillary information gives us confidence in identifying the acceptance of regular, scheduled intermittence together with unexpected delays and water quality issues, and responses to them as 'coping frame'.

Comparing household and expert views, it became clear that local experts paid little attention to the time, effort, and resources spent on managing water resources at household level, and seemed unaware that households' concerns were more about water quality and reliability, rather than water quantity. In fact, local experts mentioned household water use (Link 1a) hardly at all. If they did, they remarked that water could be saved and instead was lost due to wasteful user behaviour. For households, their user behaviour was not wasteful, but involved efforts and resources spent to generate sufficient water flows. Although local experts may have referred to only certain groups of households that supposedly use water profligately, it illustrates how such perceptions can shape problem–solution frames: Here, households are framed as part of a problem to be managed, rather than as part of the solution. At the same time, the signals that households directly received from (or sent to) the system offered them little insights into the SETS and its challenges. For example, households opined grey water recycling to be beneficial for enhancing household water availability. However, local managers could not support this, as their experience cautioned them; sewage water was already so concentrated due to the low production of wastewater that it caused frequent blockages and sewer line bursts: an insight that household respondents were unaware of. Also, grey water use can impair water quality due to pathogen loading (Al Arno et al., 2022). Together, these results suggest that local and international experts did not account for households' efforts and perceptions in their problem–solution frames.

Finally, we observed that the stakeholder groups' perspectives corresponded with different time-scales: International experts were concerned about *medium- to long-term issues*, involving large-scale investment projects that would benefit water availability through efficiency gains. Households perceived the *day-to-day* challenges of making water supplies last, coping with delivery delays and health concerns resulting from water contamination. Local experts perceived deficits regarding the maintenance of the weekly water delivery schedule, fast response to pipe bursts, and meeting the steady rise in demand for new pipe connections in the medium term. These diverging time horizons and problem–solution frames indicate a larger water management challenge:

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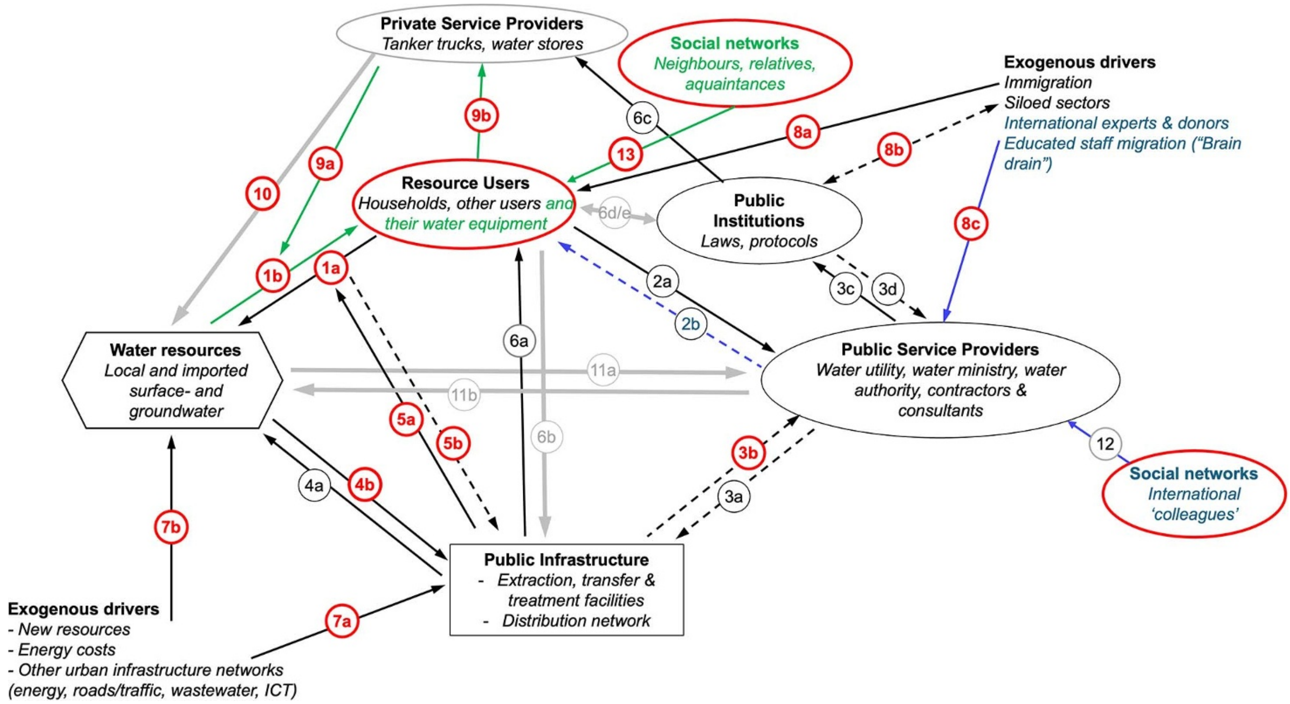

Figure 6. SETS as perceived by the three stakeholder groups. Black links represent interactions identified by local experts, blue are additional links perceived by international but not by local experts, and green links are additionally perceived by households but not by local nor international experts. Dashed links were perceived as weak or missing. Bold numbers and outlines (red colours) indicate sources of uncertainty. Grey arrows indicate links not mentioned by any of the stakeholder groups and are added for completeness.

They point to uncertainties that are immanent to the system, as they arise from different stakeholder views.

4.5. Uncertainties resulting from perception gaps

Figure 6 combines the three stakeholder perspectives shown in Figure 2–4, presenting the SETS as a whole, and Table 1 presents an overview of all system interactions as described by the three stakeholder groups. Local experts are ultimately responsible for managing and intervening in the system in order to maintain urban water resilience. Thus, we propose that links not perceived by the local system managers can indicate sources of uncertainty (highlighted in red as bold numbers and outlines in Figure 6), which we identify and categorize according to three types, as suggested by Zandvoort et al. (2019).

First, *ontic* uncertainties arise from exogenous drivers that impact the urban water system in unpredictable, non-linear ways. For example, the exploitation of new resources to supplement existing water supplies is determined externally by political decisions or economic fluctuations impacting construction and energy costs (Link 7b), refugees fleeing neighbouring conflicts increase population unpredictably, and outside decisions, such as international donor priorities, influence the water sector (Links 8a–c). As a subset of ontic uncertainty, behavioural uncertainty (Lovreglio et al., 2016; Stavrakas et al., 2019) influences household behaviour. It results from social network interactions among neighbours, including water-lending, and variable water deficits, complemented or not through the private water market.

Second, the majority of uncertainties we found were *epistemic* uncertainties. The role of private service providers, water delivery deficits, and adaptation efforts remained opaque to the experts because of a lack of metering and monitoring (indicated by the absence of Link 5b) and data deficits about the functioning of the Infrastructure (Link 3b). These epistemic uncertainties are evidenced by the divergent and unacknowledged perspectives not only between the three stakeholder groups, but also within these groups:

(a) Issues of inequality are not coherently acknowledged: Half of the local experts ($n = 6$) opined that water was supplied equally, while the other half ($n = 7$) and most international experts ($n = 4$) acknowledged that inequality of water supply was a problem, while the remaining two had no opinion. In comparison, 87% of households thought that inequality posed a problem for urban water supply resilience. In addition, our data showed that water supply durations ranged from 0.5 to 7 days per week, with a median of 2 days (standard deviation: 1.5 days); average household income was 240 Jordanian Dinar (JD)/month for low-income households and 858 JD/month for high-income households, which affected the affordability of tanker truck water; and water storage capacities varied between 3.4 and 6.2 m^3 per household. Thus, although the utility also offers water deliveries from tanker trucks at reduced prices, the wait list for such truck deliveries is long, and our results are in line with previous research highlighting the inequality of water services (Gerlach & Franceys, 2009; Klassert et al., 2015; Potter et al., 2010).
(b) Private water supply remained opaque to the water managers: Although local experts mentioned the licensing of private water suppliers and the sanctioning of illegal abstractions (international experts did not, Link 6c), relatively little attention was paid to the private water market in water management

strategies – a situation that remains today (pers. comm., 2024). Local experts stated that there were around 1500 licensed private tanker trucks. Yet, although water for public and private services is extracted from the same sources, experts had little knowledge of the demand and financial incentives to privately extract water resources (Link 10), and therefore how much water was actually extracted – legally or illegally (tanker trucks sourced their water from both formal and informal sources, including wells extracting water illegally or exceeding licenced amounts; Yoon et al 2021). When prompted during the interviews, local experts were split regarding its role and importance: While some opined that the tanker truck water market was a challenge ($n = 6$), the rest disagreed ($n = 4$), was undecided ($n = 1$), or had no opinion on the issue ($n = 4$). Those who thought this was a problem identified two issues: (1) the private water market was not regulated regarding water pricing, which can be a problem for low-income households, and (2) water quality supplied by tanker trucks was not monitored. The experts also had little insights into who needed tanker truck water. Local experts assumed that the tanker market allowed water provision during disruptions of the pipe network, as well as complementing water supply in higher income neighbourhoods. International experts saw it as beneficial for poor households, who did not have enough storage capacity and needed to refill their tanks more frequently. Our survey results indicated that both low- and high-income households bought water delivered by tanker trucks and paid prices ranging from 1 to over 12 JD per cubic meter (m^3, exchange rate 2015: 1 JD = 1.4 USD), whereas the price paid for piped water supply was well under 1 JD/m^3. This means that the private water market is strongly incentivized by high demand and revenues, and despite its important economic and resource-consuming role, it is undervalued by the experts.

(c) Experts had little insights into household-level water-related decisions and coping strategies: They did not mention the efforts spent by households to cope with varying levels of service by accessing and enhancing water resources (Link 1a), and using physical adaptations to in-house infrastructure and social support (family, friends, and neighbours, Link 13). They lacked knowledge about how water restrictions, rationing, low water pressure (Link 5a), and water provision by tanker trucks and water stores (Link 9a) affected households' water use and coping strategies, including the price paid for this water (Link 9b). Given the water scarcity situation, and in contrast to the lived experience of household survey respondents, many local experts discussed how water rationing had advantages over continuous supply; they thought that it encouraged residents to use water economically. They were concerned that continuous water supply would create a false sense of abundance and incentivize profligate water use. Our survey results showed that despite the already low water availability, over 70% of households saw the potential to save an additional 10–30%, if necessary. Thus, most households were well adapted to low water quantity, and they were more concerned with water quality and temporal reliability issues. As a result of intermittence and adaptations to it, including different water sources, experts did not know the quantity and quality of water flows (Link 1b) received by households. Only around 10% of households drank piped water without prior in-house treatment, even though local experts assured water quality, monitored by the Ministry of Health, to be in good and continuously improving condition. As one expert interviewee stated: '[Jordan's water managers] are committed to providing their residents with clean water, or none at all.' Supporting this, sampling by government officials showed that piped water was of high quality (local expert interviews and pers. comm., 2024), and it remains unclear whether the quality impairments perceived by households stem from public infrastructure deficits, from water sitting in (ill-maintained) household-rooftop storage tanks exposed to the sun and local contamination pathways, or simply from a lack of trust in the system. The different perspectives between households and experts may indicate that experts experience water supply and the private management efforts it involves differently than the majority of our survey respondents, who are not wealthy enough to employ housekeepers to take care of water-related issues around the house (see the SI for details) and are therefore acutely aware of when and how water arrives. While this creates epistemic uncertainty regarding household-level water usage, it also contributes to frame uncertainty.

Third, *frame* uncertainty results from deviating and unaccounted for frames of households, local and international experts, which aggravate epistemic uncertainties and make them more difficult to tackle. This is indicated in Figure 6 in red outlines around Resource Users and Social networks. Local managers seemed to assume that water quantity was the main concern, while household concerns and adaptation efforts were focused on maintaining continuity and water quality. Local experts seemed to have a general view of needing to maintain a centralized water supply and sanitation system that delivers safe-to-drink water from the source, rather than ensuring water quality at the tap, and flushes waste with precious water that water users would rather save for other uses. Furthermore, in line with their coping frame, households considered the water price too high, whereas with their deficit and efficiency frames local and international experts considered them as too low, with revenues insufficient to cover operational costs. However, those responsible for setting the tariffs were hesitant to do so, in fear of social unrest that could result from increasingly unaffordable living conditions, indicating that they judged household perspectives adequately in this case. However, international experts fund and support improvements of the water system, driven by their different goals and perspectives (Link 12 to Social network and Links 8 from Exogenous drivers). While the discourse introduced by international experts and resulting tensions around the New Public Management paradigm discussed above may or may not be recognized by both sides, unrevealed differences in goals and perspectives contribute to frame uncertainty. Thus, diverging frames hamper stakeholder collaboration and co-management (Zandvoort et al., 2017) making it difficult to reduce epistemic and frame uncertainties.

4.6. Characterizing new SETS interactions

Amman's intermittent water supply system operates under extreme pressure to accommodate increasing demand while constrained by deficits, including finances, infrastructure, and water resources. This situation draws attention to system elements and interactions that have previously not been considered in the SETS framework. Anderies et al. (2019) identify Link 1a as 'extraction' of Water by Users. However, we refer to 'usage', because in Amman 'extraction' is only done by public and private water suppliers, not by households (Links 6a and 10). The new/modified links that we identify

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for the Amman SETS (6a,c,d,e, 9a,b, and 10–13) contribute to the typology of SETS proposed by Anderies et al. (2019) by expanding it with an urban archetype operating under the severe ecological, social, and technological constraints and exogenous pressures. On the one hand, accounting for these links can help reduce epistemic uncertainty about the system and its interactions. On the other hand, these links can also indicate irreducible sources of ontic uncertainty, and of frame uncertainty, given that they are recognized and characterized differently by the different stakeholder groups.

5. Discussion: towards resilience-oriented water management in water-scarce cities

Amman has shown impressive resilience in the face of challenges that other world regions, including those where international experts and donor organizations typically stem from, have little experience with. Thus, despite the constraints that Amman's water managers operate under and the deficits in services that may result, the impressive resilience of this system may also hold lessons for international experts to learn from as they move into more water-stressed regimes. This resilience has emerged from a combination of local expert knowledge on how to maintain a system that is under constant pressure, investment and institutional support from international experts and donors, as well as household-level adaptations that create a buffer and mobilize (largely unaccounted for) capacities to balance service deficits at the user end.

At the same time, and typical for urban contexts in the Global South, Amman's water system is characterized by resource deficits and is confronted with large uncertainties. Taking an 'engineering mindset' typical of conventional water management approaches (Meijerink, 2005), the involved experts are trying to maintain a system through adaptation, while growing demand and dwindling water resources, degrading infrastructure, and repeated shocks gradually erode resilience (Klammler et al., 2018; Krueger, Borchardt, et al., 2019; Krueger et al., 2022). This mismatch was manifested in the fact that around 40% of water available at the city level was lost in the distribution system, while more efforts were spent on acquiring funding and negotiating contracts for new investment projects that, in the best case, would increase water availability by 30% – water that would need to be used only once to prevent sewers from blocking. Awareness of household perspectives and actions could provide valuable insights to local and international experts for maintaining and transforming the current system. However, growing demand for water resources and new pipe connections, and sewer blockages prevented local experts from investing in transformative change for a system that would be more feasible for the long term. For example, a modular system that is more adaptable to changing demands and rapid growth, and operates in a more decentralized, circular system of supply, storage, (re-)use, and treatment. Thus, transformative change, while seemingly imperative, has been impeded by a tension between rapid demand growth, resource and efficiency deficits, and by *ontic, epistemic*, and *frame* uncertainty, which mutually reinforce each other. Borrowing loosely from Biggs et al.'s resilience principles (Biggs et al., 2012), we highlight the implications of our findings for resilience-oriented management in terms of what to manage, how, and by whom:

(1) What to manage? Interacting slow and fast variables and connectivity: Contradicting 'modern' ideals of centralized water systems, the 'water bricolage' (Frick-Trzebitzky et al., 2023) of diverse, and public and private economies, including supplies through tanker trucks and household storage systems, remained largely 'under the radar' of local and international experts. Several parallel systems have emerged that are interdependent with and, if under-managed, can potentially undermine the public water service system (Links 9a, 9b, 10) by competing with, rather than complementing it. Managing the *connectivity* between these parallel or 'bricolage' systems requires resolving some of the epistemic uncertainties resulting from missing information about water and financial flows in both the public and the private water supply systems. It also requires embracing the different timescales of *interacting slow and fast variables* at play: Responding to *short-term* emergencies and rapid demand growth, planning for *long-term* investments, and resolving legal issues and institutional efficiency gains, while also acknowledging *short-term*, day-to-day coping by households. Not acknowledging the efforts taken by households to cope with deficient services may hide these deficiencies and the resulting, slowly growing private water services.

(2) How to manage?: Group-specific frames highlight the need for *social learning and experimentation* (Biggs et al., 2012) because they increase uncertainty in managing urban water systems. In particular, we observed several sources of *epistemic uncertainty* that were related to missing information exchange between experts and households, or local experts lacking insights into private water supply structures. The experts in our study were mostly concerned with changing practices and actions to meet existing goals, such as increasing water availability, reducing water demand through rationing, or enhancing efficiency. However, for successful adaptation and transformation of resource governance systems, social learning must take place on deeper levels, beyond the question of whether we are doing things right. Instead underlying assumptions must be questioned ('Are we doing the right things?'), and underlying beliefs, values, and worldviews must be revisited ('How do we know what the right thing to do is?') (Biggs et al., 2012; Pahl-Wostl, 2009). While it can take major shock events, such as socio-environmental disasters, to trigger asking such deeper-level questions, previous research has shown that a realization of uncertainties can also be a cause for seeking input from other perspectives and knowledge holders (Meijerink, 2005).

In light of the diverse elements that combine to create a heterogeneous water system in Amman, our findings further support notions of experimentation and learning that occur in the context of an adaptive governance (Folke et al., 2005) that embraces 'modest imaginaries' (Lawhon et al., 2023). Modesty in this context means to accept water management challenges like heterogeneity and uncertainty by weaving 'modernist practices' (here, Western water management expertise and efficiency frames) into 'emergent infrastructural configurations' (Lawhon et al., 2023). Including diverse knowledges in this way can be instrumental for transformative change as it allows diverse actors to 'grow ideas and actions which were unforeseen from the outset' (Chambers et al., 2022). Jordan's rich landscape of local and international knowledge holders, a population experienced in dealing with water shortages and service deficits, and a growing international community (both voluntary and involuntary migrants/refugees) bringing with them a diversity of knowledge bear the potential to sprout new ideas for experimentation and sustainability-oriented learning (Fry et al., 2024).

(3) Who manages? Embracing broad participation: Modest approaches might draw more expert attention to the fact that

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in many places, households are already participating in water-resilient management, although their participation has never been formally invited or acknowledged. Thus, instead of framing households as part of the problem to manage, if households were made part of the solution-seeking process, experts may have a lot to learn from their perceptions. To broaden participation might then imply paying attention to water users' highly resilient, creative, but also unequal and precarious coping strategies. If acknowledged in this way, the diverse and extensive adaptation efforts that households employ complement and extend public services by and into households where water is stored, treated, and reallocated among households in a form of 'co-management' (Huitema et al., 2009, Pahl-Wostl et al., 2007).

Finally, overcoming siloed management of sectors and involving stakeholders outside of the water sector can be instrumental to addressing urban nexus challenges across water-energy- and urban planning sectors (Fry et al., 2024). Involving water user knowledges and perspectives in urban system governance processes, and reframing SETS management in more situated ways based on multiple and diverging stakeholder views can shed new light on resilience strategies required for transformative change in water-scarce and unequal cities (Rodina et al., 2024). Mutual learning across stakeholder groups and unveiling underlying knowledges, values, and goals could lay the foundation for dialogue on what kind of changes are needed, invite external perspectives, and adapt them to the local context and its place-based values and views. This could provide new perspectives on what is to be managed, how, and by whom, by understanding 'what matters to whom' (Chambers et al., 2022).

In that sense, resilience-oriented water management necessitates going beyond conventional scientific and managerial views to incorporate a variety of stakeholder insights. Transformative change can be achieved through organized dialogues, scenario-driven methods, and adaptable interventions. Nonetheless, it is essential to prioritize inclusivity, manage power dynamics, and address conflicting agendas to promote sustainable and equitable water governance.

6. Conclusions

Urban water managers are faced with the difficult question of how to maintain the resilience of urban water systems in the context of various pressures and uncertainties. Here, we show that urban water systems are sensitive not only to ontic and epistemic uncertainties like changing climatic conditions or water demands, missing data, and information exchange about water abstractions and deliveries, but also to frame uncertainties in terms of how the system, its problems, and potential solutions are perceived. These frames explain why actors and stakeholder groups respond differently to system changes and dynamics. The different forms of uncertainty matter in water-scarce contexts faced with resilience challenges, as they can mutually reinforce each other and even undermine resilience-oriented water management. We do not claim that any of the different stakeholder perceptions, knowledges, and frames are more factual or relevant than others. Instead, we aim to reveal these differences and point at unaccounted-for SETS interactions and resulting uncertainties that can aggravate existing water resilience challenges through the emergence of shadow markets. Thus, we highlight the importance of acknowledging, accounting for, and integrating different knowledges and perceptions, including those of local water users, into the adaptation of water management strategies.

The empirically rich analysis of stakeholder perceptions in Amman's water system revealed key principles of resilience needed to transform this system, and potentially other water-scarce and rapidly growing urban water systems, toward greater sustainability and resilience. First, slow variables must not be ignored by local water managers, including gradual infrastructure degradation, demand growth/dwindling water resources that are strongly affected by an emerging 'bricolage' system, and inefficiencies resulting from legal and institutional bottlenecks. To avoid a sudden collapse of the system, managing the connectivity between private and public water services is urgent. Second, to enable learning on deeper levels, it is necessary to acknowledge and question underlying assumptions about what the problem is and what feasible solutions are. Allowing experimentation rather than implementing model solutions seems particularly promising in water-scarce cities where multiple endogenous and exogenous pressures increase uncertainties in water management. Third, broadened participation through the systematic inclusion of diverse knowledges is key to and offers untapped potential for fostering resilience in water-scarce urban contexts. We acknowledge that facilitating participation, rather than closing down debate in order to avoid tensions is not an easy task and will open up conflicts that unavoidably emerge from bringing together different perspectives (Chambers et al., 2022). However, the resilience of Amman's water system depends not only on managerial knowledge and infrastructural adaptations. Instead, it relies on diverse experiences, expertise, and time horizons which need to be mediated and aligned to maintain its resilience and allow a transition to a new system state, governed by different feedback mechanisms and management paradigms.

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Competing interest. The authors E.H.K., Z.M., G.N.K., and N.S.-R. declare no conflict of interest.

Research transparency and reproducibility. Supplementary materials include the interview and household questionnaires, additional results, and the coded responses from the household survey. Due to privacy reasons, the expert interview responses are not shared publicly. Please contact the corresponding author for more information.

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