For better or worse: the influence of conflict-driven decentralization on the resilience of urban water supply infrastructure in the Middle East

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SUSTAINABLE AND RESILIENT INFRASTRUCTURE
https://doi.org/10.1080/23789689.2024.2355768

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ABSTRACT

When armed conflicts disrupt urban water supply, local communities are forced to find other ways to fulfill their domestic water needs. In this paper, we analyze the development of decentralized water infrastructure as a coping strategy during armed conflict in five cities across Iraq, Syria and Yemen. We discuss the implications of conflict-driven decentralization on the resilience of urban water supply infrastructure, addressing its functionality, its recovery in case of disruption, and its sustainability on the long term. The results indicate that decentralized water supply systems developed throughout conflict uphold a basic level of functionality and minimize their vulnerability to conflict-related shocks. However, short-term resilience gains come at the cost of health risks and high water prices, and undermine system sustainability due to a lack of coordination. We conclude that decentralization processes implemented within the constraints of armed conflict are often detrimental to infrastructure resilience, particularly over longer timeframes.

ARTICLE HISTORY
Received 5 May 2023
Accepted 10 May 2024

KEYWORDS
Critical infrastructure; decentralization; resilience; armed conflict; Middle East

1. Introduction

Sustainably managed urban water supply systems are crucial for public and environmental health, as well as for economic activity. The disruption of water supply can have far-reaching consequences, particularly if systems cannot be restored in a timely manner. Highly-interconnected critical infrastructure systems and high population density in cities can lead to reverberating effects and the deterioration of multiple basic services throughout the area (Pescaroli & Alexander, 2016; Vespignani, 2010).

Armed conflicts combine a high likelihood of infrastructure damage with obstacles to infrastructure restoration (Talhami & Zeitoun, 2021; Wille & Borrie, 2016; Zeitoun, Elaydi, Dross, et al., 2017). Conflict impacts on critical infrastructure and their consequences for basic service provision are particularly severe in protracted conflicts, i.e., prolonged armed conflicts that shift between periods of high and low conflict intensity and involve various armed actors. In these settings, infrastructure damage and basic service disruptions accumulate over time and water supply infrastructure is often exposed to multiple episodes of high-intensity conflict before an effective, system-wide recovery is possible (Hay, Karney, & Martyn, 2019; J. Sowers & Weinthal, 2021; Zeitoun & Talhami, 2016). Resilient water infrastructure is therefore essential to mitigating severe humanitarian crises.

In this paper, we go beyond the analysis of initial infrastructure damage to investigate how urban water supply infrastructure changes throughout armed conflict as a result of local coping strategies to uphold water supply. Previous studies on conflict-affected settings pinpoint the spontaneous development of decentralized water infrastructure as a common approach to cope with service disruption and other water access restrictions at the community level (Aklan, Fraiture, & Hayde, 2019; Roach & Al-Saidi, 2021; Zeitoun, Elaydi, Dross, et al., 2017). Building on these studies, we connect the de/centralization of urban water supply infrastructure throughout armed conflict to infrastructure resilience. Throughout this paper, we use the term 'de/centralization' when referring to the general concept, describing a spectrum ranging from centralized supply, in which few water providers serve many consumers each, to decentralized supply, in which a larger number of interconnected water providers serve fewer consumers each, reducing the dependency of consumers on a single provider. We use the terms 'centralization' or 'decentralization' when referring to processes which shift the system towards the respective side of the spectrum (Helmrich, Markolf, Li, et al., 2021).

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/23789689.2024.2355768

Specifically, we address two research questions: 1) How does the degree of de/centralization before the conflict affect the performance of water supply systems and the coping strategies available to local communities during armed conflict? 2) How does the ad-hoc decentralization of water supply infrastructure during armed conflict influence the resilience of the urban water supply system in the short and long term? We aim to contribute to the literature on critical infrastructure and urban service provision in armed conflict settings by broadening the scope of conflict impacts. To this end, our analysis includes not only the external shocks in the form of infrastructure damage and service disruption (such as Faour & Fayad, 2014; Weinthal & Sowers, 2019; Zeitoun, Eid-Sabbagh, & Loveless, 2014), but also the coping strategies of actors within the infrastructure system.

In addition, we seek to provide broader insights on infrastructure resilience in highly unstable settings, by exploring lessons that can be drawn from the coping strategies in conflict settings and inform action in other contexts affected by critical infrastructure or basic service disruption, for instance due to disasters. The analysis of local dynamics linked to community coping strategies may further help identify entry points and opportunities for humanitarian actors to effectively address local needs and build on community-based water management processes (Hay, Karney, & Martyn, 2019). Finally, we develop a conceptual framework that incorporates new dimensions of infrastructure resilience and water management in conflict-affected settings. Such frameworks have rarely been applied for analyzing water management during armed conflict, which limits the feasibility of comparative studies and the generalizability of empirical results (Schillinger, Özerol, Güven-Griemert, et al., 2020).

Our analysis centers on water supply throughout armed conflict in five Middle Eastern cities: Aleppo in Syria, Mosul and Ramadi in Iraq, and Sana'a and Hudaydah in Yemen. We focus on domestic water supply to households as a fundamental humanitarian need during armed conflicts, leading to the quick application of coping strategies as soon as previous water supply structures fail.

The remainder of this paper is structured as follows: We first review the literature on de/centralization of water supply and critical infrastructure resilience to develop our framework for the analysis of urban water supply infrastructure during armed conflict. Next, we describe our methodology and introduce the five cities that serve as case studies in the analysis. We then compare the cases with regard to conflict impacts on their water supply systems and the ad-hoc decentralization processes employed as coping strategies in each city, before discussing the implications of these decentralization processes for infrastructure resilience. We conclude the paper with key insights, implications for humanitarian actors and potential avenues for future research on critical infrastructure in armed conflicts.

2. Conceptual framework

2.1. De/centralization of urban water supply

Modern urban water supply infrastructure is highly centralized in many parts of the world, including in the Middle East. Centralization allows for efficient, and thus low-cost, water service provision making use of economies of scale, and has served to professionalize service provision and introduce new technologies under the leadership of a central, often state-owned, utility (Leigh & Lee, 2019). Centralized water supply systems can also be linked to the need for significant water transfers from beyond the urban area (Hoekstra, Buurman, & van Ginkel, 2018). At the same time, centralized systems have been criticized for their lack of flexibility and adaptability to changes in demand patterns or the hydrological cycle, for instance due to climatic changes. Their dependency on large-scale infrastructure, including major water treatment plants and extensive pipe networks, causes high maintenance needs and potential points of failure that can severely affect the entire system (Chester & Allenby, 2019; Helmrich, Markolf, Li, et al., 2021; Leigh & Lee, 2019; Rabaey, Vandekerckhove, van Walle, et al., 2020). In other words, systems characterized by centralized governance structures and physical infrastructure are 'designed for a low probability of failure' and 'best equipped to manage known, rather than unknown, disturbances' (Helmrich, Markolf, Li, et al., 2021, p. 6).

Given this limited capacity of centralized systems to deal with uncertainty in future water use, as well as the significant environmental footprint of most large-scale infrastructure related to energy use, waste production and soil sealing, decentralized urban water supply infrastructure has increasingly been discussed in the context of resilience and sustainability (Leigh & Lee, 2019; Rabaey, Vandekerckhove, van Walle, et al., 2020; Vázquez-Rowe, Kahhat, & Lorenzo-Toja, 2017). Advantages of decentralized water supply systems include reduced upfront investment for small-scale infrastructure, the possibility to diversify water sources, redundancy or modularity in the network design which can limit cascading failures, and a high adaptability to local contexts (Helmrich, Markolf, Li, et al., 2021; Leigh & Lee, 2019; Makropoulos & Butler, 2010).

When analyzing the de/centralization of physical urban water supply infrastructure, we distinguish between three stages of water supply: abstraction, treatment, and distribution. The water abstraction stage comprises the abstraction of water from surface or groundwater resources, and the production of non-conventional water resources, e.g., desalinated water or treated wastewater. In a highly centralized water supply system, one abstraction facility, e.g., a groundwater well, serves the entire system, whereas in a highly decentralized system, each user has access to their own water source. The local hydrological and geological conditions affect the degree of de/centralization that is feasible for a water supply system. The water treatment stage includes the purification of water to ensure that it is safe to use. In a centralized system, this happens in one central treatment facility, which may be part of a combined abstraction and treatment station. At the other extreme, highly decentralized water treatment occurs at the point of use, i.e., the household level in the case of domestic water use. In the water distribution stage, we can differentiate between water distribution via a fixed pipe network, or in mobile fashion by use of water trucks or portable storage containers like jerry cans. In the case of pipe networks, the degree of decentralization increases with the level of redundancy in the network design and the independence from specific water mains. De/centralization of mobile water distribution primarily depends on the availability of different service providers and the availability of filling points at which fixed and mobile distribution interface. Depending on the degree of de/centralization, most water distribution happens before (decentralized treatment) or after (centralized treatment) the purification, with implications for required water quality safeguards during distribution, e.g., to avoid the contact with pollutants after treatment (Baecher, 2006; Makropoulos & Butler, 2010).

De/centralization and scale of water supply systems are often discussed in tandem, as centralized systems typically entail large-scale water resources development and service provision, while decentralized systems comprise small-scale facilities and development patterns (Leigh & Lee, 2019; Makropoulos & Butler, 2010). In our analysis of physical infrastructure, de/centralization refers to the overall design of the infrastructure system as outlined above, whereas scale refers to the coverage area or size of the system or specific facility, including possible economies of scale.

2.2. Water supply and de/centralization in conflict settings

Armed conflicts are likely to impact water supply systems in three main ways. First, infrastructure damage to water facilities and the municipal network disrupts service provision or affects water quality downstream of the damaged infrastructure. In the case of highly centralized infrastructure systems, damage to one central facility can disrupt water services to large parts of the city (Schillinger, Özerol, & Heldeweg, 2022; Sowers, Weinthal, & Zawahri, 2017). Second, armed conflicts often severely decrease the operational capacity of public utilities, due to a lack of funds to operate and maintain infrastructure, an increased cost of service provision linked to high energy prices, and a lack of qualified staff caused by brain-drain and displacement (Pinera, 2012; Schillinger, Özerol, & Heldeweg, 2022; Zeitoun, Elaydi, Dross, et al., 2017). Third, changes in territorial control throughout the conflict can obstruct water service provision in highly centralized infrastructure systems. Where water facilities are captured opposing conflict parties, access for staff and repair crews can be impeded, and infrastructure is at risk of being weaponized, for instance to cut water supply to certain conflict areas (Daoudy, 2020; Lossow, 2016). These vulnerabilities also apply to other critical infrastructure that is required for water service provision, such as major power plants.

Considering their flexibility, decentralized water supply systems are commonly seen as more resilient to conflict-related shocks than centralized systems (Donnelly, Ha, Cooley, et al., 2012; Roach & Al-Saidi, 2021; Zeitoun, 2005). However, development organizations caution that decentralization processes in fragile settings should be well-implemented and accompanied by capacity-building measures to ensure sufficient local resources and knowledge and to prevent the capture of decentralized decision-making by local elites and armed groups (Food and Agriculture Organization of the UN [FAO] & World Bank, 2018; Huston & Moriarty, 2018). In contrast to this ideal scenario, transitions towards decentralized systems during armed conflict often occur as ad-hoc coping strategies in reaction to local conflict impacts with limited or no system-level coordination, such as the community-led restoration of local water service provision (Al-Saidi, Roach, & Al-Saeedi, 2020; Zeitoun, Elaydi, Dross, et al., 2017). Decentralization in these cases is not a conscious design choice, but rather a consequence of the limited capacity of local populations to (re)construct or manage large-scale infrastructure in the absence of public service providers or authorities. Given the unconventional nature of this decentralization, its implications for the resilience of urban water supply systems are questionable. Before we dive deeper into this question, we first clarify the term 'resilience' in the context of critical infrastructure systems, particularly during protracted conflicts.

2.3. Critical infrastructure resilience

Considering the resilience of infrastructure systems acknowledges that it is impossible to protect them from all external or internal shocks. Instead, infrastructure systems should be able to cope with a certain level of localized disruption without significant impact on system-level performance while the initial problem is being resolved (Ahern, 2011; Kim, Eisenberg, Bondank, et al., 2017). In the critical infrastructure literature, resilience is therefore often defined in terms of two components: the capability to withstand a shock and maintain functionality, and the capability to recover quickly after the shock where needed (Cantelmi, DiGravio, & Patriarca, 2021; Chang, McDaniels, Fox, et al., 2014; Osei-Kyei, Tam, Ma, et al., 2021). Decentralization by means of modularization and redundancy of the infrastructure system is a common design strategy to increase resilience (Ahern, 2011; Helmrich, Markolf, Li, et al., 2021). Beyond the focus on short-term recovery from a shock, resilience can also be seen as a long-term, dynamic process in which a system reacts to slow onset events, for example related to climate change (Krueger, Borchardt, Jawitz, et al., 2019; Sage, Sircar, Dainty, et al., 2015). From this perspective, critical infrastructure resilience connects to wider conceptualizations of urban resilience, which consider the ability of urban systems to withstand disturbances and adapt to gradual changes over time (Elmqvist, Andersson, Frantzeskaki, et al., 2019). The adaptive capacities of critical infrastructures and of the communities that depend on them influence the resilience of urban service provision, particularly related to coping strategies that are available to communities in case of public service disruption (Krueger, Rao, & Borchardt, 2019). The complexity of urban systems, infrastructures and management processes can additionally lead to trade-offs between short-term and long-term resilience objectives, the full implications of which may only manifest in the long run (Chelleri, Waters, Olazabal, et al., 2015).

Over the past three decades, studies on critical infrastructure resilience have primarily considered threats related to natural hazards, to cyber security and terrorist attacks, and to cascading failures in highly interconnected critical infrastructure systems, particularly in densely populated urban areas (McDaniels, Chang, Peterson, et al., 2007; Osei-Kyei, Tam, Ma, et al., 2021; Rinaldi, Peerenboom, & Kelly, 2001). Literature specifically on the resilience of urban water infrastructure has focused on three types of hazards: natural hazards with a low frequency and large-scale consequences, e.g., earthquakes; operational failures with high frequency and localized consequences, e.g., pipe failures leading to contamination; and imbalances between supply and demand due to rapid urban growth (Liu & Song, 2020). Hazards related to political instability or armed conflict are seldom considered. This is further compounded by the geographic focus of the scholarly literature on critical infrastructure resilience, which predominantly studies stable, industrialized countries (Osei-Kyei, Tam, Ma, et al., 2021).

While infrastructure resilience during armed conflict has rarely been studied within the critical infrastructure field, it is an emerging research theme at the intersection of conflict studies and resilience studies (Adelaja, George, Fox, et al., 2021; Contreras & Contreras, 2016; Shapira, 2022). The small body of literature related to infrastructure limits relevant conceptualizations and empirical evidence. Roach and Al-Saidi (2021) provide a first attempt to operationalize the conflict resilience of infrastructure systems using multiple criteria, including both micro-level vulnerability of system units and macro-level resilience of the whole infrastructure system. They consider highly centralized infrastructure as vulnerable to strategic targeting of central facilities, and decentralization as a potential means to increase conflict resilience through participatory and localized basic service provision. However, the same group of authors also notes elsewhere that highly decentralized infrastructure can become fragmented, making it more difficult to manage, reducing the potential for synergies and hindering a coordinated reaction to conflict-related shocks across the system (Al-Saidi, Roach, & Al-Saeedi, 2020).

2.4. Water supply infrastructure resilience and de/centralization in armed conflict

We synthesize conceptual insights on water supply systems, de/centralization and infrastructure resilience to analyze the influence of conflict-driven decentralization on the resilience of urban water supply infrastructure. For this purpose, we develop the framework shown in Figure 1, which incorporates the linkages among de/centralization, interconnectivity and scale of water infrastructure. We also consider the role of the mobility

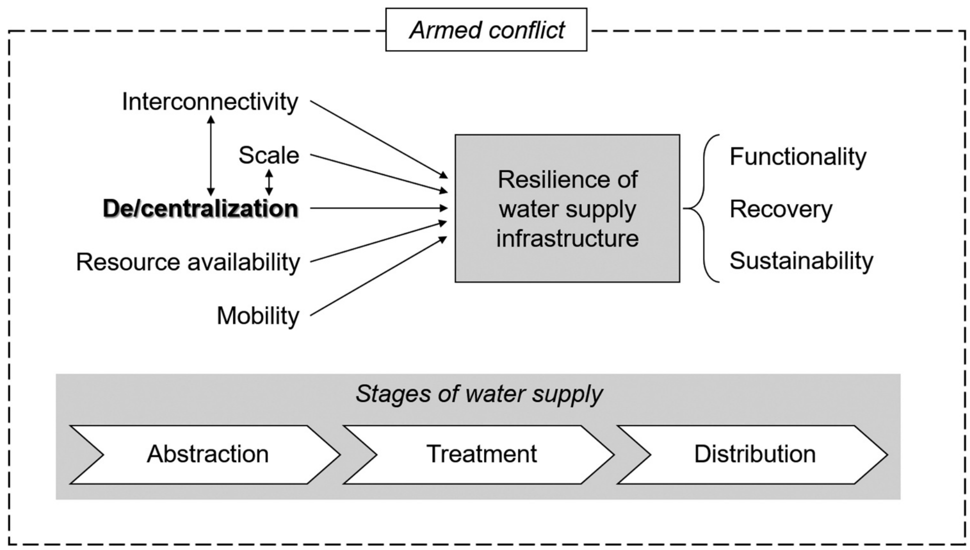

Figure 1. Conceptual framework of conflict-driven decentralization and the resilience of water supply infrastructure in the context of armed conflict.

of infrastructure and the availability (or lack) of resources that are necessary for the operation and maintenance of infrastructure during conflicts, both of which were identified as determinants of resilience in conflict settings by Roach and Al-Saidi (2021). While we primarily analyze coping strategies with regard to changes in the de/centralization of water supply infrastructure, we also expect implications for these related factors. For instance, alternative infrastructure may be of a smaller scale or constructed to be more mobile than previous infrastructure (Roach & Al-Saidi, 2021). These dynamics are analyzed across the three stages of water supply – abstraction, treatment and distribution –, showing how decentralization processes occur and affect existing infrastructure systems at each supply stage throughout the conflict. Differentiating between these stages allows us to pinpoint conflict impacts and coping strategies, and to draw meaningful conclusions on conflict-driven decentralization processes at different points in the water supply chain.

We discern three elements of water supply system resilience to analyze the implications of infrastructure changes during armed conflict on the short and long term: functionality, recovery, and sustainability. Functionality is the ability of the system to provide continued access to water regardless of shocks. It covers the vulnerability of water supply facilities to conflict-related shocks, in terms of both infrastructure damage and broader operational capacity, as well as their ability to function if other infrastructure fails. Functionality also addresses the continued accessibility of water services, e.g., related to water prices during conflict (Krueger, McPhearson, & Levin, 2022). Recovery is the ability of the system to quickly restore functionality when disrupted, including the needs of different system elements for their recovery, and the feasibility of meeting these needs in the current conflict setting (Cantelmi, DiGravio, & Patriarca, 2021; Osei-Kyei, Tam, Ma, et al., 2021). Finally, the sustainability of the water supply system relates to the system's long-term viability as well as potential social and environmental impacts that could jeopardize its resilience (Krueger, Borchardt, Jawitz, et al., 2020). The usefulness of combining the concepts of resilience and sustainability has been a topic of discussion within the field of resilience studies (Anderies, Folke, Walker, et al., 2013; Elmqvist, Andersson, Frantzeskaki, et al., 2019; Redman, 2014). We opt to make the explicit link between the two concepts based on the characteristics of water supply systems, the functioning of which require water resources of sufficient quality and quantity. The future resilience of the urban water supply system therefore depends on the sustainable use of the water resources it was built upon, or its flexibility to pivot to alternative resources if needed.

3. Methods

Our analysis is based on longitudinal case studies of five cities: Aleppo in Syria, Mosul and Ramadi in Iraq, and Sana'a and Hudaydah in Yemen (Table 1). In each case study, we analyzed the water infrastructure and urban water supply before, during and, where applicable, after armed conflict, including different periods of high and low conflict intensity and major turning points in the conflict that affected the water supply system. The

Table 1. Overview of pre-conflict demographic characteristics and access to water services in the case study cities.

City	Primary conflict period[a]	Pre-conflict population estimate (2010)[b]	Approximate urban area (2010)[c]	Pre-conflict coverage of municipal water network and frequency of supply
Aleppo, Syria	2012–2017	3,078,000	135 km^2	94%, 20 h per day (2009)[d]
Mosul, Iraq	2014–2017	1,175,000	180 km^2	>90% (2011), no data on frequency[e]
Ramadi, Iraq	2015–2016	208,000	40 km^2	>90% (2011), no data on frequency[e]
Sana'a, Yemen	2014–2022	2,084,000	135 km^2	48% (2014)[f], 8 h per day, one day per week (2013)[g]
Hudaydah, Yemen	2018–2022	489,000	60 km^2	75% (2017)[f], 24 h per day (2013)[g]

[a]*The time period indicated here reflects the main case study period and high-intensity conflict period in each city. Due to the protracted nature of the armed conflicts at hand, additional conflicts outside of the indicated period are possible.*
[b]UN-Habitat (2021).
[c]*Approximate size of the built-up urban area, based on* Wang, Huang, Brown de Colstoun, et al. (2017).
[d]UN-Habitat (2014).
[e]*In the absence of specific data on the municipal water network coverage in Mosul and Ramadi, coverage is estimated based on the UNICEF Multiple Indicator Cluster Survey 2011, in which 99% of surveyed urban households reported to receive piped water supply directly to their house or to their plot in both Mosul (n = 247) and Ramadi (n = 147) (UNICEF, Central Statistics Organization Iraq, & Kurdistan Regional Statistics Office of Iraq, 2011).*
[f]*Gesellschaft für Internationale Zusammenarbeit [GIZ] (2018).*
[g]*GIZ (2014).*

comparison of these five cases allows us to draw conclusions on commonalities and differences between the infrastructure systems throughout conflict and to investigate implications for infrastructure resilience in different settings.

The cases were selected based on multiple criteria. They are all major cities in the Middle East, and, prior to the respective conflicts, had urban water systems of similar development status that were facing common challenges related to a lack of capacity and largely outdated infrastructure, due to insufficient maintenance and population growth. The cities also played important roles in the armed conflicts within their countries and saw prolonged high-intensity conflict within the urban area, leading to significant infrastructure damage and forcing local populations to employ various coping strategies to maintain water access. At the same time, the urban water supply infrastructures in the five cases exhibited different degrees of de/centralization prior to the conflict, and were fed from different types of water resources, i.e., surface water or groundwater.

The primary conflict periods which are studied in each case differ in duration and patterns of high and low conflict intensity, mirroring the diverse nature of conflict settings. This allows us to explore possible implications of different conflict dynamics and the various ways in which they affect urban water supply infrastructure. In addition, the extensive infrastructure assessments that provide data for our analysis are often impossible during periods of high intensity conflict and can only depict their aftermath. The range of conflict durations therefore also provides a larger set of snapshots of the development of alternative water infrastructure through time. Section 4 highlights key differences in the respective conflict dynamics when describing the five case studies, particularly for cases within the same country.

Data collection in conflict settings is notoriously difficult, with significant limitations on the availability and reliability of data sources (Barakat, Chard, Jacoby, et al., 2002; Cronin-Furman & Lake, 2018). For our five cases, data was primarily collected through document review, including project reports and situation assessments by humanitarian and development organizations working in each city and by other governmental and non-governmental organizations. Where possible, this desk-research data was verified and contextualized with interview data, including 11 interviews conducted with water sector stakeholders in Mosul and Ramadi in February 2021, and transcripts of 15 interviews conducted with water sector stakeholders in Yemen between December 2017 and January 2018.[1] The qualitative analysis of these materials provided insights on the status of urban water supply infrastructure, living conditions and coping strategies at different points in time throughout each conflict.

4. Case study descriptions

Urban water supply in many parts of the Middle East, including Iraq, Syria and Yemen, struggles with the combination of physical water scarcity and insufficient organizational capacity, for instance related to the mandates of public agencies and the coordination among them (Al-Saidi, 2020). As a result, large disparities persist in the quality and continuity of water supply across the region and within countries, including highly variable network connection rates in cities, particularly in poorer or informal urban areas which are commonly not connected to the municipal network (FAO, 2018). Where network connections are available, water supply can still be intermittent, with gaps as long as several weeks. This forces households to store water at home or use alternative water service providers, and can have significant impacts on water quality (Kumpel & Nelson, 2016; Simukonda, Farmani, & Butler, 2018). High rates of non-revenue water and low bill collection rates further undermine the financial viability of water supply systems and the associated utilities (Al-Washali, Sharma, Al-Nozaily, et al., 2019; FAO, 2018). Increasing urbanization and population growth across the region are expected to further exacerbate these issues in the coming decades (Borgomeo, Fawzi, Hall, et al., 2020).

Accordingly, urban water supply in all five cases was already challenging prior to the outbreak of armed conflict, often related to significant population growth over the past decades, which pushed the urban water supply system past its capacity. Table 1 provides an overview of the pre-conflict access to public water services in each city.

4.1. Aleppo, Syria

Aleppo's water supply infrastructure has historically been highly centralized, with ca. 90% of the water coming from a water treatment plant on the western shore of Lake Assad, 80 km west of Aleppo (UN-Habitat, 2014). Upon arrival in Aleppo, two central pumping stations distribute the water across the municipal network, one station serving most northern, western and southern neighborhoods, the other serving the Old City and most eastern neighborhoods (World Bank, 2017).

As political unrest turned into civil war in Syria, Aleppo became one of the fiercest battlefields between the government and opposition armed groups. From the opposition forces first capturing territory within Aleppo in summer 2012 until the Syrian government re-established full control in late 2016, Aleppo was split into a government-controlled western part and an opposition-controlled eastern part (UN Human Rights Council, 2013). The different conditions between Western and Eastern Aleppo are reflected in their modes of water service provision and coping strategies. In Western Aleppo, damage to water infrastructure was limited, and the government and municipality continued operating the centralized public sector and water service provision (World Bank, 2017). In Eastern Aleppo, widespread infrastructure damage and disruptions in the electricity network led to the deterioration of the water supply system. Basic services were provided by various actors, including the opposition-run city council, neighborhood councils, private service providers and humanitarian organizations (UN-Habitat, 2014; World Bank, 2017). Damage to the water network and electricity shortages impeded service provision via the municipal network in many areas, leaving residents to rely on boreholes in their neighborhoods, often with insufficient water treatment, and on trucks to deliver water over longer distances (REACH, 2014b, 2015; UNICEF, 2016).

The conditions of territorial control throughout the conflict further complicated water supply in war-torn Aleppo. With both central pumping stations located in Eastern Aleppo, armed opposition groups gained control over the stations and, consequently, the water supply to Western Aleppo (UNICEF, 2016). The situation was worsened in February 2013, when the so-called Islamic State of Iraq and Syria (ISIS) advanced along the western shore of Lake Assad, capturing the area including Aleppo's water treatment plant (Mazlum, 2018).

The Syrian government re-established control over all of Aleppo in December 2016, and re-captured the western shore of Lake Assad in March 2017 (Institute for the Study of War, 2017). Major water infrastructure was restored relatively quickly in 2017, whereas the water network was more difficult to rehabilitate, with an estimated 84% of the pipe network damaged during the conflict. By 2019, most of Aleppo had regained access to the municipal water network, although water was rationed and households needed to store water at home. As part of the governmental-led infrastructure rehabilitation plans, alternative water sources to Lake Assad were to be explored (Urban Analysis Network – Syria [UrbAN-S], 2019).

4.2. Mosul, Iraq

Mosul's public water supply is based on a series of pumping and treatment stations along the Tigris River, each serving a specific part of the city. While fairly decentralized, the infrastructure had also become outdated and unable to serve the rapidly increasing population of Mosul in the early 2000s (Human Appeal, 2018; UN-Habitat, 2016). Additional pumping and treatment stations had been constructed to increase the system's capacity in the years prior to ISIS gaining control over Mosul, however, their operation was limited by a lack of electricity and qualified staff (REACH, 2016a).

ISIS captured Mosul in June 2014, causing an estimated 500,000 inhabitants, or one-third of the city's population at the time, to flee within the first two days of ISIS control (Ahmed, 2014). For those who did not manage to leave the city, service provision, including water, deteriorated, with unreliable access to piped water and insufficient water treatment (Beauchamp, 2014; REACH, 2016a, 2016b). Instead, people started to rely on makeshift neighborhood wells, which they would often reach by foot, and the limited treatment methods available to them at home (Zucchino & Solomon, 2017).

The military operation to liberate Mosul from ISIS lasted from October 2016 until July 2017, with the Iraqi military and their allies first recapturing East Mosul by January 2017, and then advancing on West Mosul. With increasing conflict intensity throughout the battles, West Mosul, particularly the Old City, suffered the heaviest infrastructure damages (UN Assistance Mission for Iraq, 2017; UN-Habitat, 2017a). The restoration of Mosul after the liberation has been a very slow process, including the reconstruction of the municipal water network, which sustained significant damage. Domestic water supply strategies employed during the occupation therefore remained in use until at least 2018 (Lafta, Cetorelli, & Burnham, 2018; UN-Habitat, 2019).

4.3. Ramadi, Iraq

Ramadi's public water supply infrastructure combines decentralized abstraction from pumping stations along the Euphrates River with centralized treatment in three facilities, all located in al-Warrar neighborhood alongside other public utilities. A small number of public water tanks provide storage capacity throughout the city (UN-Habitat, 2018).

While ISIS' capture of Mosul was rather sudden and caught many people by surprise, the advance towards and capture of Ramadi had been expected by many of the city's inhabitants. When ISIS established control over Ramadi in May 2015, several hundred thousand people had already left (UNICEF, 2015). Over the following months, water treatment deteriorated significantly due to the lack of operational capacity in ISIS-controlled Ramadi. Access to water from the municipal network became unreliable or non-existent, with the low water quality making the water unsuitable for most domestic uses (REACH, 2016a).

The month-long military campaign to liberate the city from ISIS brought heavy fighting to the streets of Ramadi throughout December 2015. By the time the Iraqi military had re-established control at the end of the month, an estimated 80% of all buildings in Ramadi were damaged or destroyed (Fessy, 2015; Hubbard, 2016). This included the water treatment plants in al-Warrar neighborhood, forcing households to use water filters at home while the central water treatment capacity was restored. The reconstruction of Ramadi's water infrastructure advanced relatively fast, with most neighborhoods regaining access to piped water by spring 2017, although water quality remained problematic, necessitating continued household-level water treatment (REACH, 2016c, 2017b).

4.4. Sana'a, Yemen

Sana'a, Yemen's capital, stands out among the five cases due to the role of the private sector in urban water supply: private water service provision already had a larger market share than public service provision prior to the current conflict (Foppen, Naaman, & Schijven, 2005; Zabara, Babaqi, Abu-Lohom, et al., 2010). Throughout the city, a network of more than 200 wells produces groundwater, with an approximately even split between wells by the local utility and privately owned wells. Water treatment was decentralized, with a mix of major sterilization facilities, treatment at well level and small businesses offering water purification services. Next to the municipal network, private water service provision by truck was very common, particularly in the informal outskirts of the city (Abu-Lohom, Konishi, Mumssen, et al., 2018). Decades of unregulated expansion of private groundwater abstraction had already led to severe overexploitation of the local resources and the groundwater table dropping by several meters each year (UNICEF & Oxfam, 2016; Weiss, 2015).

Following the onset of armed conflict between Yemeni president Abdrabbuh Mansur Hadi and the Houthi movement (Ansar Allah), the Houthis declared themselves in control of Sana'a and key government buildings in September 2014, and further expanded their influence over local governance and the violent repression of dissent over the following months (Ghobari, 2014; Salisbury, 2017). The conflict escalated with the involvement of a Saudi-led military coalition in support of Hadi starting in March 2015, after which Sana'a became a regular target of airstrikes (UN-Habitat, 2020b). At the same time, water production from municipal wells dropped by ca. 65% (GIZ, 2018). The city experienced an additional conflict escalation in late 2017, when the alliance between the Houthis and former president Ali Abdullah Saleh broke, leading to several days of fighting in the streets of Sana'a (Rogers, 2020).

Throughout the periods of high and low conflict intensity, private water service provision by truck has strongly increased in the absence of piped water. Residents have additionally made increasing use of public standpipes to fetch water for domestic use and implemented household-level rainwater harvesting (Aklan, Fraiture, & Hayde, 2019; UNICEF & Oxfam, 2016).

Water trucks are now also used for water distribution by the local utility and by the civil society organizations active in the area (Abu-Lohom, Konishi, Mumssen, et al., 2018; UN-Habitat, 2020b).

4.5. Hudaydah, Yemen

Hudaydah's urban water supply is fed by two well fields outside of the city, whereby the Al-Baydda well field directly north of the city supplies water to ca. 70% of the city's households. The transmission of water to the city through centralized treatment facilities and pumping stations creates potential bottlenecks in the system. At the same time, large reservoirs at the pumping stations provide storage capacity to buffer supply irregularities in water supply. Most of the municipal network is outdated, having been constructed in the early 1980s when the population was less than 200,000, and suffers from the build-up of salt in the pipes (GIZ, 2018; UN-Habitat, 2020b).

The Houthis took control of Hudaydah in October 2014 and held the area, including Hudaydah's well fields, with little resistance until late 2017. Due to the relatively calm situation in Hudaydah, the city received many internally displaced people, putting pressure on the water supply system (World Bank, 2020).

Pro-Hadi forces began a military offensive along the Red Sea coast to re-capture Houthi-controlled territories in late 2017, reaching Hudaydah in June 2018. A fierce battle ensued over the city, during which pro-Hadi forces managed to capture many areas south and east of Hudaydah, but not the city itself. The well fields remained under Houthi control as well. A ceasefire agreement was eventually signed in December 2018, which led to a decrease in conflict intensity, but failed to stop the fighting entirely (UN Office for the Coordination of Humanitarian Affairs, 2018; UN-Habitat, 2020a). Infrastructure damage from the initial offensive and the fighting since then has affected an estimated 60% of water, sanitation and hygiene facilities as of March 2020 (DW, 2018; World Bank, 2020), with damage to one of the central pumping stations in July 2018 temporarily cutting off water to 85,000 households (Bottomley & Salavert, 2020).

5. Results and discussion

Based on these five cases, we first identify and compare conflict impacts on the different types of water supply systems, and analyze ad-hoc decentralization as a coping strategy along the three stages of water supply. We then present and discuss the influence of these decentralization processes on water infrastructure resilience, and reflect on the role of community agency and adaptive capacity in the application of different coping strategies during armed conflict.

5.1. Development of alternative water supply systems throughout armed conflict

The five cities included in this paper exhibited different degrees of de/centralization across the three stages of water supply prior to the conflicts, and, except Sana'a, were dominated by public service providers.[2] Coping strategies in all cases include the establishment of new or expansion of existing alternative water supply systems with higher degrees of decentralization than the public supply infrastructure. However, challenges and coping mechanisms differ between cities and across the three stages of water supply. Below, we discuss the characteristics and implications of conflict-driven decentralization in each stage.

5.1.1. Water abstraction

We can distinguish three groups of water abstraction infrastructure among the five cases: 1) Aleppo and Hudaydah, with large-scale abstraction facilities located outside of the city, necessitating centralized transmission of water towards the city; 2) Mosul and Ramadi, with multiple medium-scale abstraction facilities located along surface water resources within the city; and 3) Sana'a, with a network of numerous groundwater abstraction facilities throughout the city.

The urban water supply infrastructure system in groups 1 and 2, where public water supply is dependent on medium- or large-scale abstraction infrastructure, was specifically designed around these facilities. They are highly vulnerable to disruption by conflict impacts, be it due to direct infrastructure damage, loss of operational capacity or access to electricity, or changes in territorial control. Alternative water sources are usually incompatible with this existing public supply system, as they are not connected to the municipal network. Consequently, once public water abstraction facilities break down, the rest of the public system, including treatment and distribution facilities, loses its functionality to a great extent.

The dependency on the continuous availability of the water resource is another vulnerability of water abstraction infrastructure. The loss of water access, for instance due to a rapid decline in groundwater table, as has been observed in Sana'a for the past years (UNICEF & Oxfam, 2016), either renders abstraction facilities dysfunctional or requires adjustments that are prohibitively expensive during a high-intensity armed conflict. Surface water availability can further be limited by the weaponization of dams along major rivers, as in the case of Ramadi, which was affected by a decrease in the Euphrates River flow after ISIS captured several dams upstream and within Ramadi itself (Alkhshali & Smith-Spark, 2015; Paletta, 2016).

Due to a combination of conflict impacts, public water abstraction significantly declined soon after the onset of high-intensity conflict in Mosul, Ramadi and Sana'a (groups 2 and 3), and the conditions of territorial control made the supply of water from Lake Assad unreliable for Aleppo (group 1). This led to the development of alternative water sources and matching decentralized supply systems for these cities.

Both Mosul and Aleppo saw the widespread operation of neighborhood wells by local residents from early on in the respective conflicts (see e.g., Tawfeeq & Abdelaziz, 2016; Zucchino & Solomon, 2017 for Mosul, and International Committee of the Red Cross [ICRC], 2015; REACH, 2014a, 2015; UNICEF, 2016 for Aleppo). These wells were either part of pre-existing, but deteriorated well networks across the city, particularly in Aleppo, or newly constructed using the means available. Due to the low water quality and a lack of on-site treatment, water from these wells was usually not potable, but still used for most domestic purposes.

The switch from surface water to groundwater as primary resource was observed in all cases that relied on surface water prior to the conflict, even if the surface water resource is locally available, like in Mosul and Ramadi. While rivers provide an opportunity for decentralized public water abstraction with multiple pumping stations along the banks, the municipal water network is needed for efficient distribution. Once the network is damaged or otherwise dysfunctional due to the ongoing conflict, the distance between most households and the river becomes prohibitively long, as water often has to be carried by hand and residents might have to cross areas of high-intensity fighting. As long as groundwater resources are available, neighborhood wells can be placed closer to the households, providing easier and safer water access. A survey conducted among households in Mosul shortly after the liberation from ISIS showed that 100% of surveyed households in the eastern part of the city (as of March 2017) and 91% of surveyed households in the western part (as of July 2017) used local wells as their primary source of water for domestic use, with very limited use of the river itself (Lafta, Cetorelli, & Burnham, 2018).

Sana'a provides the example of a city that was already served by a decentralized network of groundwater wells, including both public and private facilities. Rather than seeing a significant transition in abstraction infrastructure like in the cases in Iraq and Syria, Sana'a experienced a rapid expansion of the private water sector. This included an increase in the use and number of private wells, as well as an increase in the number of private service providers (Abu-Lohom, Konishi, Mumssen, et al., 2018; Aklan, Fraiture, & Hayde, 2019; World Bank, 2020).

The transition towards decentralized, private or community-managed water abstraction facilities affects the monitoring processes that are in place to ensure adequate water quality and sustainable abstraction rates. As institutional capacity to enforce environmental and health regulations is already diminished during armed conflict (Schillinger, Özerol, & Heldeweg, 2022), the lack of centralized information on alternative water abstraction facilities further obstructs monitoring and enforcement further. Access to adequate water treatment is therefore important to avoid health risks related to low water quality.

5.1.2. Water treatment

Centralized water treatment plants are typically large-scale facilities serving a significant amount of water users, such as in Ramadi, making them vulnerable to the same kinds of disruptions related to infrastructure damage and loss of operational capacity as abstraction facilities. Water abstraction and treatment may also occur in the same facility, like in Aleppo and Mosul, meaning that a disruption would affect both stages of water supply. In addition, regardless of scale or de/centralization, the continued functionality of water treatment facilities depends on the availability of treatment chemicals, particularly chlorine, which are often severely restricted in conflict settings (Schillinger, Özerol, & Heldeweg, 2022; Zeitoun, Elaydi, Dross, et al., 2017).

With the onset of high-intensity conflict, water treatment largely transitioned to the most extreme form of decentralization, the point-of-use water treatment at household level. This is not only due to the loss in centralized treatment capacity from water treatment plants, which could be compensated for by water treatment systems of a smaller scale. Instead, a key factor in the complete decentralization of water treatment is the high likelihood of damage to the municipal pipe network, which allows pollutants to enter the network between water treatment and point of use. The lack of clear enforcement of water quality standards in the distribution of water by trucks further necessitates water treatment directly prior to its use. In all three countries, household-level water treatment is not uncommon outside of high-intensity armed conflict either. A UNICEF survey in 2011, for instance, concluded that 51% of households in Mosul and 79% of households in Ramadi treated the water they received from the municipal network, often by using water filters (UNICEF et al., 2011).

The quality of household-level water treatment depends on the means and knowledge available to residents. Common household-level treatment methods reported by humanitarian organizations in the five cities include boiling water, treating water with chlorine, and using basic filtration (REACH, 2016c, 2017a, 2017b; UN-Habitat, 2020a). The lack of access to treatment chemicals or suitable filters was regularly mentioned as a key driver of household water insecurity in humanitarian needs assessments (Iraq Assessment Working Group, 2017; REACH, 2014a; Water and Environment Center, MetaMeta, & Flood-Based Livelihoods Network Foundation, 2017). The highly decentralized nature of household-level water treatment complicates monitoring processes, as the quality of water used for domestic purposes varies between households based on their available treatment options. This variation can, for instance, affect the proper attribution of health issues in public health assessments during conflict.

The restoration of the pipe network to the point of ensuring sufficient water quality is usually the most difficult and lengthy part of water supply system restoration. Consequently, water treatment stays decentralized to the household level for significant time periods after high-intensity conflict ends, as observed for example in the case of Ramadi, where households had to continue point-of-use treatment despite the quick reconstruction of most water infrastructure.

5.1.3. Water distribution

The pipe network is the most efficient approach for distributing water across an urban area, with the exception of informal settlements in peri-urban areas like in the case of Sana'a. However, network functionality depends on three key factors that are easily disrupted during armed conflict: the continued inflow of water from an abstraction facility; the structural integrity of the network to uphold pipe pressure; and the availability of electricity or fuel to power pumps at key nodes. We already discussed the challenges for public water abstraction facilities during conflict, and the shift towards alternative, decentralized abstraction, which is often incompatible with the existing pipe networks and needs to be distributed by other means. Commonly located underneath streets, pipe networks are exposed to infrastructure damage from airstrikes on road networks and vehicles, as well as from the operation of heavy vehicles on the street (Schillinger, Özerol, & Heldeweg, 2022). Widespread damage to the municipal water network was observed in Mosul, Ramadi and Aleppo, testament to the high intensity of fighting within the cities (UN-Habitat, 2017b; UrbAN, 2019). Where networks remain largely undamaged, electricity or fuel shortages can render them dysfunctional, as observed in Sana'a and Hudaydah (GIZ, 2018; Water and Environment Center et al., 2017; World Bank, 2020). Access to electricity is often limited in ongoing conflicts, and fuel prices soar as local communities, utilities and armed forces compete for fuel to fulfill their energy needs.

In areas where the pipe network is partially functional and serving public water points, water can be distributed in a hybrid way – by pipe network until the water point, and by mobile distribution for the rest of the way to the user. A high density of such points allows residents to collect water from within walking distance, and to switch to a different point if needed, leading to a highly decentralized and flexible distribution. The construction of such water points can be difficult during conflict and often depends on the financial and technical support of humanitarian organizations. Ideally, the urban water supply infrastructure therefore already includes a dense network of water points prior to the conflict.

Where the pipe network is entirely dysfunctional, or alternative water sources are not connected to the network, mobile distribution becomes essential, sometimes covering significant distances. This is also the case where mobile water distributers, e.g., private water trucking companies, have access to their own private wells and can circumvent the municipal system entirely, such as in Sana'a (Abu-Lohom, Konishi, Mumssen, et al., 2018; UNICEF & Oxfam, 2016). Using water trucks for mobile distribution is common in areas where the construction of pipe networks is uneconomical or impossible for other reasons (Constantine, Massoud, Alameddine, et al., 2017). As such, all cases already had some degree of water distribution by truck in underserved or informal neighborhoods prior to the onset of armed conflict. However, with the deterioration of the municipal pipe network, the use of water trucks significantly increased. These trucks provide a high degree of flexibility in water distribution, as they can switch to a different water source if needed. At the same time, their operation can be restricted during high-intensity conflict, as road networks might be damaged and access to fuel becomes difficult and expensive. Security concerns further limit the options for mobile distribution in areas of active fighting, as was reported for different parts of Hudaydah in 2018 (Slemrod, 2018).

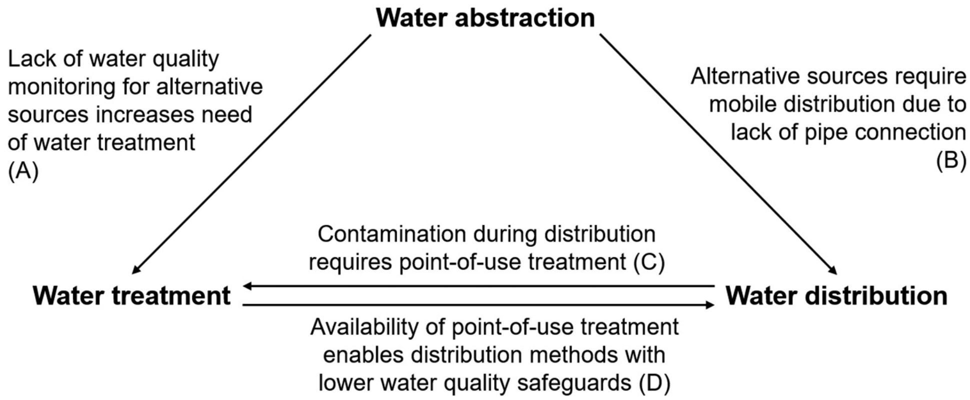

Figure 2. Linkages between the three water supply stages, whereby the conflict-driven decentralization of infrastructure at one stage necessitates adjustments at another stage. Letters A-D refer to corresponding examples explained in the text.

5.1.4. Linkages between the water supply stages

While the separate analysis of the three water supply stages has allowed us to identify specific conflict impacts, coping strategies, and their implications for infrastructure systems at each stage, there are also important linkages between them. The decentralization of infrastructure at one stage often necessitates an adjustment of infrastructure or management processes at the other stages. Figure 2 provides an overview of such links, using four illustrative examples. The decentralization of water abstraction through the development of alternative sources, most notably makeshift wells, has implications for both treatment and distribution. The water quality from such sources can often not be ascertained, as monitoring is difficult in a decentralized web of small-scale wells or water points, increasing the need for treatment to ensure safe water use for households (A). Since most alternative sources are not connected to the pipe network, water can only be distributed by mobile means, such as trucks or jerry cans (B). The relationship between the de/centralization of treatment and the quality safeguards required in water distribution were previously discussed. In conflict-affected settings, particularly when mobile distribution methods are used or pipe networks are damaged, contamination during the distribution stage is likely, necessitating point-of-use treatment at the household level (C). Inversely, where households already have access to point-of-use treatment methods, distribution means with lower quality safeguards, such as unregulated water trucks, become less problematic (D).

The linkages between the three stages also imply that a coordinated restoration of abstraction, treatment and distribution infrastructure is required to fully restore the water supply system. While post-conflict reconstruction efforts typically focus on central water abstraction or treatment facilities, the positive effect of such interventions on safe water access is limited unless distribution systems are restored at the same time.

5.2. Conflict-driven decentralization and infrastructure resilience

After exploring and outlining the different dynamics of conflict impacts and conflict-driven decentralization across the urban water supply system, we now circle back to the question of infrastructure resilience. While the alternative water supply systems developed in the five cases increased household water access during the respective conflict compared to the dysfunctional public water supply system, their long-term consequences are less clear. Here, we analyze the implications for the resilience of urban water supply infrastructure regarding its functionality and recovery in the short term, and its sustainability in the long term.

5.2.1. Functionality

Several characteristics of alternative, decentralized water supply infrastructure alleviate its vulnerability to disruption due to conflict-related shocks. The small scale of many facilities reduces their exposure to infrastructure damage. They are also a less attractive target for deliberate attacks,[3] as the overall impact on the water supply system is significantly smaller than in the case of a large-scale, centralized facility. In addition, makeshift decentralized infrastructure, such as neighborhood wells, is typically constructed with materials that are locally available during the conflict. This makes such infrastructure less dependent on imported materials for routine maintenance or repairs. However, the restriction to locally available materials also means that subpar materials might have to be used, affecting efficiency and increasing the risk of malfunction.

To maintain functionality, many water facilities depend on continued access to consumable materials, most notably fuel for generators and water treatment chemicals. Some of these consumables remain available during the conflict via local markets, while others need to be provided by external actors. Point-of-use water treatment in particular often relies on humanitarian organizations to provide household water treatment kits. As a conflict becomes protracted and donor fatigue sets in, or conflict parties restrict humanitarian access, the availability of such materials can become limited, leaving households with only basic methods of water treatment.

The vulnerability to cascading failures is limited, particularly in relation to energy infrastructure. As most alternative water supply infrastructure is constructed or put back to use after the conflict has already started to disrupt electricity supply, facilities are commonly outfitted with small generators to provide the required electricity (Zucchino & Solomon, 2017). They are independent from the central electricity grid and can function regardless of further disruptions to it. However, they do depend on access to fuel for the generators, whose availability can vary throughout the conflict. The use of solar panels as primary power source can further reduce this dependency (Coerver, Ewers, Fewster, et al., 2021). Mobile distribution systems like water trucks allow for high flexibility and fast reaction to spatial changes in water availability, e.g., depending on functional filling points, and in water demand, e.g., due to the displacement of residents from areas of high-intensity fighting. Possible limitations to the functionality of such mobile distribution systems are linked to the accessibility of different parts of the city via the road network and the availability of fuel.

The cost of water service provision in the alternative decentralized water supply systems often increases sharply due to their strong dependency on expensive fuel. Additionally, small-scale decentralized systems cannot benefit from the same economies of scale that allow for relatively cheap service provision in large-scale, centralized water supply systems. Local residents are therefore faced with increasing water prices that can limit their access to water services. This is particularly pronounced in areas where water service provision is taken over by private companies, which can often operate without regulatory oversight during conflict (Aklan, Fraiture, & Hayde, 2019).

Given the increased cost of service provision, the continued operation of water services typically depends on the support from humanitarian or development aid actors. The implementation of externally funded projects in collaboration with local service providers and the distribution of financial support are administratively easier in a centralized system with few contact points and centralized information systems. However, centralization also increases the vulnerability to corruption and the redirection of funds within the central body. In contrast, a diverse landscape of decentralized service providers is more robust to corruption risks, as not all funds are received by the same entity, but requires more administrative work to navigate. Where comprehensive information on local service providers is lacking, key providers may accidentally be excluded from support programs.

Similarly, information about suitable water sources is more difficult to compile and share with local communities in a decentralized system without central oversight of the numerous wells or water points. In Aleppo, this challenge gave rise to a large-scale campaign by the International Committee of the Red Cross (ICRC) to map and communicate the location of safe wells to the public (ICRC, 2015; Shaheen, 2015).

In summary, the decentralized water supply systems developed throughout conflict largely uphold a basic level of functionality, by using small-scale applications that minimize the risk of infrastructure damage, staying independent from the electricity grid, and applying mobile and flexible means of water distribution. The deterioration of pre-conflict water treatment capacity and water quality concerns linked to distribution systems can, to some extent, be compensated by point-of-use water treatment at the household level. At the same time, high water prices and a lack of information can restrict water access to parts of the community.

5.2.2. Recovery

A number of factors that reduce the vulnerability of decentralized water supply facilities to conflict-related shocks also contribute to their fast recovery in case of disruption. The use of locally available materials facilitates the access to materials needed for repair works. The independence from the electricity grid further allows water facilities to resume operation regardless of the current status and potentially needed restoration of electricity infrastructure, as long as the local power source is operational.

For the recovery of system-wide functionality, coordinated reconstruction of infrastructure across all three water supply phases which accounts for water supply realities on the ground is needed. As previously mentioned, this means that reconstruction efforts need to go beyond the central water abstraction or treatment facilities that are often targeted in recovery projects, and include distribution networks. Additionally, reconstruction efforts should take note of new alternative water supply infrastructure and the actors involved in their operation, and identify implications for the system recovery. In some cases, the inclusion of the alternative water facilities into the post-conflict supply system might make sense, as a way to decentralize urban water supply infrastructure. This can also extend to strengthening the position of private water service providers in the post-conflict period, particularly in areas like Sana'a, where their share in the urban water market increased considerably throughout the conflict (see also Pinera & Reed, 2009).

Overall, the technical restoration of water supply infrastructure is easier in a decentralized system of small-scale facilities, as recovery can proceed step by step, while already restoring functionality in sub-systems. At the same time, the recovery effort benefits from central leadership to ensure coordinated progress. In the absence of sufficient government or other local capacity to provide this leadership and coordination, external actors like humanitarian organizations can intervene. Irrespective of the actor taking charge, leading an effective recovery process requires detailed knowledge of the local water supply infrastructure and of specific challenges related to coping strategies and possible externalities. The lack of centralized information on ad-hoc infrastructure development is a key challenge in this process.

5.2.3. Sustainability

The uncoordinated and unregulated development of alternative urban water supply infrastructure throughout armed conflict, particularly in the case of water abstraction, is likely to exacerbate issues of water insecurity on the longer term. Overabstraction from unmonitored decentralized water infrastructure threatens the sustainability of supply systems based on groundwater resources, as can be observed in Yemen. Both Sana'a and Hudaydah, dependent on local groundwater resources for their supply, suffer from overexploitation, a long-term issue to water management in both cities that has been exacerbated by conflict. Consequences for the urban supply systems include significant drops in the groundwater table, necessitating deeper, more expensive wells, and new groundwater quality challenges linked to seawater intrusion in coastal areas and the hydrogeological characteristics of deeper aquifers (UNICEF & Oxfam, 2016; Visscher, Al-Washali, Al-Nozaily, et al., 2021).

The makeshift nature of many alternative water facilities may have negative side effects. Such externalities can result from the use of unsuitable building materials that cause pollution, for instance when pipes or tubing that previously carried contaminated water are being reused. The fuel-powered generators that many facilities rely on to stay independent from the electricity grid additionally cause localized air and noise pollution. Deteriorated equipment can further lead to fuel leaking into the soil and local water resources (Coerver, Ewers, Fewster, et al., 2021).

These results match patterns of so-called 'harmful coping strategies' that have been observed to pose a threat to sustainability in conflict settings. They describe coping strategies which adversely affect human security or risk the long-term deterioration of basic service provision and livelihoods in favor of short-term relief, for instance due to the overuse of local water resources or the sale of livestock and other productive assets (Mallett & Slater, 2012; Munas & Lokuge, 2016).

Post-conflict reconstruction provides an opportunity to incorporate effective decentralized structures into previously centralized public water supply systems to improve the accessibility and resilience of urban water services on the long term. Such improvements can target physical water infrastructure as well as management processes, whereby the latter may include community-led management, public-private partnerships or increased involvement of the private sector in water supply to build alternative service provision capacity in case of renewed conflict (Pinera & Reed, 2009). However, the uncoordinated nature of conflict-driven decentralization and the consequential lack of centralized information on new water facilities and management processes limits the possibilities for this integration.

5.3. Community agency and adaptive capacity

Communities and other informal actors play a central role in the conflict-driven decentralization of water infrastructure, which warrants a brief discussion of their agency and adaptive capacity during conflict. Earlier studies on urban water supply showed that community adaptation is a key determinant of water access in poor and underserved urban areas, and that a lack of adaptive capacity significantly increases communities' vulnerability to water insecurity (Krueger, Borchardt, Jawitz, et al., 2019; Waters & Adger, 2017).

Across the five cases analyzed in this paper, a range of actors were involved in developing alternative water supply infrastructure, such as private service providers in Sana'a, community-led initiatives in Mosul and a combination of private providers, residents and international organizations in Eastern Aleppo. The resources and capacity to mitigate risks and respond to conflict-related shocks differ between these actors, with implications for local water management and urban water supply. Such consequences include impacts on the operation and maintenance of facilities, the quality control of water services in the absence of formal regulatory oversight, and the access to funding for operational expenses or repair works. This was particularly visible in the contrast between government-controlled Western Aleppo and opposition-controlled Eastern Aleppo.

Research on the impacts of armed conflict on community adaptive capacity is sparse and primarily focuses on climate-related hazards (Hellin, Ratner, Meinzen-Dick, et al., 2018; Jaspars & Maxwell, 2009; Sitati, Joe, Pentz, et al., 2021). However, many factors, such as access to material and immaterial resources, economic opportunities and livelihoods, are equally applicable to conflict-affected communities' capacity to cope with the disruption of critical infrastructure and the corresponding basic services.[4] The social cohesion of a community and its potential for collective action additionally influence the range of available coping strategies and can strengthen existing initiatives. For example, in the Mosul case, interviewees who resided in Mosul during the occupation by ISIS recounted that women, who were in charge of household affairs such as water for domestic uses and hygiene, formed social networks around the available infrastructure in their neighborhood.

Social and identity-related factors such as gender or ethnicity further influence the agency of individuals or certain households, particularly women-led households (Chandra, McNamara, Dargusch, et al., 2017; Jaggernath, 2014). As a result, agency and adaptive capacity are not homogeneous across conflict-affected communities. The in-depth analysis of such patterns and their influence on localized coping strategies was, however, beyond the scope of this paper. Further research on the capacity and role of different groups in developing alternative infrastructure systems during armed conflict is needed to better understand the corresponding social dynamics.

6. Conclusion

When armed conflicts disrupt the established water supply systems in cities, residents are forced to find other ways to meet their water needs. In this paper, we analyzed the ad-hoc decentralization of water infrastructure as a coping strategy in five conflict-affected Middle Eastern cities and investigated the effects of this decentralization on the resilience of urban water supply infrastructure during and after the conflict. Our findings show that the decentralized water supply systems generally succeed in providing a basic level of water access throughout the conflict and minimize the vulnerability to disruptions due to their small scale and independence from most other critical infrastructure systems. However, concerns related to water quality and price, as well as access to information on available water sources prevail due to the absence of central oversight. The uncoordinated and unregulated development of decentralized water infrastructure can additionally have severe negative impacts on the long-term sustainability of the water system, particularly in areas where water resources are naturally scarce.

Cities with a highly decentralized water supply systems prior to conflict faced fewer challenges in developing or expanding alternative systems when public supply deteriorated, showing a higher degree of flexibility and adaptability to changes in water availability and demand. In protracted conflict settings where the renewed outbreak of violence is likely, it is therefore useful to decentralize the urban supply system where possible during reconstruction, as was initially planned for Aleppo to diversity water sources. Based on our analysis, the key physical infrastructure to support such decentralized and resilient supply systems includes a network of groundwater wells across the city, equipped with facilities for basic, on-site water treatment, and a dense grid of public water points that provide an interface between piped and mobile water distribution. In addition, the inclusion of community-led or private service provision into the urban supply system during periods of peace or low conflict intensity can build vital capacities for these actors to take over when high-intensity conflict disrupts public service provision.

For humanitarian actors engaged in conflict settings, our results emphasize the importance of context-specific interventions that account for community-led coping strategies and work within the given infrastructure configuration to improve safe access to water. The five case studies showed that enhancing household-level water treatment plays a crucial role in such situations, as it allows local communities to continue to use their alternative, more flexible and, on the short term, more resilient water infrastructure, while reducing the associated health risks.

The lack of coordination and monitoring of conflict-driven decentralization is the core of its negative impact on resilience. In conflict settings, this is largely due to insufficient institutional capacity of the authorities and public utilities. Humanitarian organizations and other external actors can, on the one hand, provide support to enhance monitoring and bridge information gaps, as observed in the case of the ICRC in Aleppo. On the other hand, the same need for coordination among actors and infrastructure projects to alleviate negative impacts on resilience applies to these external actors as well, particularly regarding the abstraction of local water resources. Disconnected humanitarian interventions, while well-intended, can have equally detrimental impacts as the uncoordinated ad-hoc decentralization by local communities. The urgency of humanitarian action needs to be balanced with an informed, context-sensitive approach to local infrastructure development.

This paper served as a starting point to explore the dynamics of critical infrastructure and water service provision in armed conflicts. As its scope is limited to urban water supply for domestic purposes, future research should broaden this scope to include water supply for other uses, particularly agriculture, and wastewater infrastructure. The conceptual framework developed in this paper is not exclusive to water supply and can also be applied to other critical infrastructure systems for which ad-hoc decentralization is a common coping strategy in conflict settings, for instance energy supply or waste management. In order to fully understand the coping strategies applied by different groups, more in-depth studies of the heterogeneous agency and adaptive capacity within conflict-affected communities are essential. In combination, such studies will further expand the evidence base on critical infrastructure processes in armed conflicts and post-conflict reconstruction, and provide valuable information on how to improve basic service provision in these settings.

Notes

1. Interview data on Yemen was collected by Musaed Aklan and Hanan Bahar in the context of another research project and kindly shared for inclusion in this study. An overview of all interviews on Iraq and Yemen can be found in the Supplementary Material.
2. An overview table on pre-conflict urban water supply infrastructure in the five cities can be found in the Supplementary Material.
3. While deliberate attacks on water supply infrastructure are prohibited under International Humanitarian Law provisions on the protection of objects indispensable to the survival of the civilian population, not all conflict parties are deterred by such provisions.
4. It should be noted here that the disruption of basic services itself is an important factor in the deterioration of adaptive capacity during armed conflict.

Acknowledgments

We thank the staff and volunteers of Humat Dijlah for their logistical support in conducting interviews in Iraq, and Musaed Aklan and Hanan Bahar for generously sharing their interview data from Yemen. JS is funded by the Heinrich Böll Foundation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the Heinrich Böll Foundation.

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Data availability statement

Interview data that supports the findings of this study is available from the corresponding author, JS, upon reasonable request.

Research ethics

This research was reviewed and approved by the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente. All interviewees provided informed consent prior to their participation.

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