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Informality in Urban Water Systems: Affordability, Energy-Water Nexus and Social Network Aspects in Beirut, Lebanon

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Abstract

Many parts of the world with chronic and intermittent water shortages rely on informal water systems for all or part of their daily water uses, such as water deliveries from water tanker trucks, purchased bottled water, or water pumped from local wells. These alternative sources tend to burden water users with additional costs, require additional energy inputs, and are managed by informal stakeholders. Using a political ecology lens and a mixed methods approach, this research examines informal water services in Beirut (Lebanon), their socio-economic and environmental impacts, and aspects of their organization. The research analyzes affordability disparities between high- and low-income communities, considering the additional costs of informal water sources and residents' different coping behaviors and capabilities. The research also assesses environmental impacts of informal water systems with a comparative energy-water nexus and carbon footprint analysis of formal (piped infrastructure) and informal water sources. The research also applies social network analysis to identify and characterize informal water tanker firms, and shows indirect socio-cultural and environmental driving forces influencing their organization, cooperation and competition. Finally, while recognizing the importance of informal services to achieve water security, the research addresses their social injustice outcomes through hybrid policy recommendations for hybrid systems that target formal piped infrastructure and informal sources to balance resilience with sustainability and attenuate the inequalities of those services.

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Chapter 1: Introduction

Urban water system research and critical analysis are diverse and typically focus on formal piped infrastructure. However, the combined pressures of climate change, population growth, and diminishing clean water resources threaten these urban infrastructure systems worldwide (Muller 2012; Farrelly & Brown 2014). Water utilities face challenges of aging infrastructure, economic and demographic changes, and ecological vulnerability (Hanak et al. 2011). And, in many areas around the world, the ability of water agencies to respond to these challenges is inhibited by mismanagement and corruption (Rogers & Hall 2003; Davis, 2004). Ultimately, the combined impact of these pressures impedes the delivery of safe and reliable water services and increases overall residential water shortages and insecurities. Around two thirds of world population (~5 billion people) experience water scarcity in at least parts of the year (Kummu et al., 2016; Mekonnen & Hoekstra, 2016; Young et al., 2019).

When formal piped infrastructure fails to deliver needed quantities and qualities of water, people resort to informal systems and supplies, including water trucks, bottled water, storage in local cisterns, or pumping water from wells (Revell 2010). Formal systems serve around 40% to 70% of urban population in the global south, while the remaining population is served by informal systems (Ahlers et al. 2014). Informal water sources tend to be managed by informal stakeholders and businesses that can be flexible and adaptable to users' demands, and can help communities overcome shocks and stresses in water system quality and reliability (Holling, 2001; Pickett et al. 2004). They may also improve the resilience of urban water supplies by increasing the adaptive capacity of the system to unexpected shocks and unpredictable changes both within the system and beyond it (Liddle et al. 2016; Trærup, 2012; Revell, 2010). However, informality is not politically, culturally, socio-economically and environmentally neutral. Informal water systems can have negative socio-economic and environmental impacts. They tend to be 4 to 30 times more expensive than formal piped systems (Wutich et al 2016), they require additional energy resulting in additional carbon emissions, and because of lack of monitoring and regulation (London et al 2021), they tend to supply lower quality water to their customers, exposing communities to health hazards (Kjellén & McGranahan, 2006). Moreover, they are influenced by informal stakeholders who manage them and control access and prices for water (Swyngedouw, et al 2002). Altogether, informal sources lead to an overall unsustainable water system, characterized by socio-economic and environmental disparities. Given the prevalence of informal water systems, and embedded tradeoff and inequalities within these systems between resilience and sustainability, it is worth analyzing their drivers and impacts. This research assesses informal water systems in Beirut (Lebanon). It provides a qualitative and empirical analysis of the affordability of such systems, their energy requirements and carbon emissions, and the informal stakeholders behind Beirut's informal water systems, and highlights some aspects of disparities between users as well as service providers.

Literature review on Informality and Gaps

Informality definitions have evolved significantly over time, as summarized in **Table 1**. Early scholars had a more dualistic and negative view on informality, while more recent scholars highlight its complexity and potential to support resilient communities**.** The concept of informality emerged in the 1970s to understand the condition of workers outside formal employment systems in Ghana and other countries in Africa. Early definitions imposed a dualistic view, separating formal and informal, and placing informality and the urban poor in the same realm (Hart, 1973, AlSayyad, 2004). Roy (2005) breaks this dichotomy describing the relationship between formal and informal as ever shifting "between what is legal and illegal, legitimate and illegitimate, authorized and unauthorized" (Roy, 2009, 80). This shows that informal systems are complex, and entangled with formal counterparts (Bakker, 2003; Misra, 2014; Peloso and Morinville, 2014). The relationship between formal and informal also is referred to as a meshwork (Schwartz et al., 2015) or as co-produced (Ahlers et al., 2014). More recent scholars highlight the positive sides of informal systems as beneficial. They are flexible and adaptable to users' demands and can help communities overcome shocks and stresses in the water system (Holling2001; Pickett et al.

2004). They can improve the resilience of urban water supplies (Liddle et al. 2016; Trærup, 2012; Revell 2010).

Table 1 - Evolution of the Concept of Informality.

Characterizing Informality		**References**
Dualistic view focuses on urban poor		Hart (1973)
A complex system	An ever-shifting system	Roy (2005)
	Entanglement with formal systems	Bakker (2003) Misra (2014) Peloso and Morinville (2014)
	Meshwork	Schwartz et al. (2015)
	Co-produced	Ahlers et al. (2014)
Positive sides of informality	Resilient system	Revell (2010) Trærup (2012) Revell (2010)
	Flexible and adaptable	Holling (2001) Pickett et al. (2004)

Scholars of informality also have looked at some socio-economic and environmental impacts of informal water sources. As summarized in **Table 2**, typical water affordability studies, that consider alternative informal water sources, tend to focus on people's access to bottled potable water (Christian-Smith et al., 2013; Moore et al., 2011; Walter et al., 2017). Rare are frameworks that evaluate the cost and affordability of accessing other water sources (mixed sources such as tankers trucks, or wells) (Nganyanyuka et al., 2014; Teodoro, 2018), capture water affordability of different income groups with a focus on lower income (Nastiti et al., 2017; Komarulzaman, 2017; Thompson et al., 2001; Jepson and Vandewalle, 2016; Pattanayak et al., 2005), or evaluate coping behavior to secure enough water (Amit and Sasidharan, 2019; Baquero et al., 2017). The combination of these frameworks is minimally evident in the literature. Furthermore, few studies analyze simultaneous affordability disparities of informal water sources for different income groups.

Table 2 - Added Cost of Informal Water Sources.

Focus	**Location**	**Reference**
Bottled water	California	Christian-Smith et al., (2013)

Bottled water	California	Moore et al., (2011)
Packaged drinking water	Indonesia	Walter et al., (2017)
Mix sources	Dar es Salaam	Nganyanyuka et al., (2014)
Water and sewer services	USA	Teodoro (2018)
Coping costs of collecting, pumping, treating, storing, and purchasing canned water.	India	Amit and Sasidharan (2019)
Cost of distance and time travelled to reach a water point	Mozambique and Nicaragua	Baquero et al., (2017)
Multiple sources – lower and middle income areas Alternative water sources – lower and middle income areas Multiple water activities – lower income areas Water Insecurity from accessing multiple sources – lower income areas Coping cost of collecting, pumping, treating, storing, and purchasing – lower and middle income areas	Indonesia Indonesia East Africa Texas-Mexico Border Nepal	Nastiti et al., (2017) Komarulzaman (2017) Thompson et al., (2001) Jepson and Vandewalle (2016) Pattanayak et al., (2005)

Environmentally, studies are limited to the analysis of water quality of informal sources. Scholars mainly focus on water contamination from unmonitored informal sources (El-Fadel et al., 2003; Kjellén & McGranahan, 2006; Constantine et al 2017), or how groundwater quality deteriorates household appliances leading to higher repair and replacement costs (Alameddine et al 2018). Almost no study includes other environmental dimensions, such as added energy requirements of informal sources and their carbon emissions.

Scholars of informal systems also have been concerned with political drivers that lead to informality. As summarized in **Table 3**, these political drivers include international donors, state powers, private organizations, as well as systemic and historical discrimination and marginalization. Moretto (2005) describes how international donors, such as the World Bank, contribute to the proliferation of informal systems in developing countries, because of their lack of understanding of and strategies for addressing the local socio-political and environmental interplay. State powers that control access to water also can lead to informality. Kooy (2014) uses the concept of governmentality to explain how administrative systems through politics of water and centralized knowledge and power were able to control who accesses improved water quality and quantities in Jakarta. Liddle et al. (2016) describes how newly independent colonies in Zambia and Ndola were ill equipped politically, socially, economically, and administratively to develop and manage water resources. Ranganathan (2014) shows how water mafias in Bangalore are state-social powers controlling who accesses water provision services, in addition to providing social protections and welfare. In areas along the Texas and Mexico borders, poorly functioning water markets and private corporations result in lack of reliable and affordable drinking water and insufficient connections to water service in low-income communities (Jepson & Vandewalle, 2016). Systemic and historical socio-political structures can produce unequal regulations. For example, in Kings' Basin, disadvantaged communities are not well integrated in the water authority's management plans, which leads to poor understanding of their needs and their inability to have access to enough funding (Balazs, and Lubell, 2014). In the San Joaquin Valley, disparities in water access are linked to spatial, racial and class-based dimensions that exclude Disadvantaged Unincorporated Communities to have proper access to drinking water and other infrastructure (London et al., 2021). And in the Central Valley, historical socio-political structures create drinking water problems for marginalized communities (Balazs & Ray, 2014).

These case studies provide a rich understanding on how informality is rooted in political drivers. Other indirect socio-cultural and environmental drivers also might be important to consider as they influence how informal stakeholder manage and control informal water sources.

Table 3 - Political Drivers That Lead to Informality.

Political Drivers		**Context**	**Reference**
International donors and their lack of understanding of local context.		Developing Areas	Moretto (2005)
State powers that control who accesses	Absence of administrative and	Zambia and Ndola	Liddle et al (2016)

water can also lead to informality	political infrastructure to manage water sources		
	Governmental administration controls water access	Jakarta	Kooy (2014)
	Water mafias controlling water access and social protection	Bangalore	Ranganathan (2014)
Water market and private corporations		Texas-Mexico Boarder	Jepson and Vandewalle (2016)
Systemic and historical discrimination and marginalization leads to unequal access to water systems	Historic socio-political structure produce unequal regulations	Central Valley, California	Balazs and Ray (2014)
	Spatial, racial and class-based dimensions lead to water access disparities	San Joaquin Valley, California	London et al (2021)
	Water authorities do not integrate disadvantaged communities	Kings' Basin, California	Balazs, and Lubell, (2014)

Other scholars have recognized roles of social relations within informal networks. They show that informality relies on human infrastructure (Peloso and Morinville, 2014; Ahlers et al., 2014) and informal activities tend to be negotiated every day (Ahlers et al., 2014; Ranganathan, 2014). Informal water allocation can be influenced by the interaction of different social and political processes. These case studies have adopted a qualitative descriptive understanding of the stakeholders behind the functioning of overall informal water systems, as summarized in **Table 4**. Empirical analysis of the organization and interaction of informal stakeholders has been rarely studied (but see Wutich et al 2016). Unlike formal institutions, understanding the social relations of informal systems and impact on water sources is challenging because of the nature of their informality, i.e. hidden characteristics and lack of regulation (Bakker, 2003). Usually, it is not easy to know who these stakeholders are, their total number, activities, and relationships. Identifying and characterizing these informal stakeholders is essential in understanding their roles in the overall governance of a water system.

Table 4 - informal water systems: stakeholders and activities.

	Misra (2014)	**Kooy (2014)**	**Liddle *et al.* (2016)**	**Cheng (2014)**
Location	Bhubaneswar, India	Jakarta, Indonesia,	Ndola, Zambia	Manila and Mayniland, Philippines
Informal stakeholders	Trucks Private firms Individual and community actors	Water hydrant operators Water trucks Water utility staff: falsification of water meter readings.	Residents	Micro-Networks comprised of: Water trucks Households Cooperatives
Informal Activities	Wells Boreholes Standpipe Tankers	Illegal Connection Shallow wells	Abstraction from streams Shallow Wells Boreholes	Groundwater Extraction

Research Focus and Case Study Area

While existing research on informal water systems is extensive and diverse, it remains insufficient. The literature is mostly limited in analyzing affordability disparities of informal water sources; in assessing energy requirements and carbon emissions of informal sources, and in illuminating stakeholders behind informal water systems and drivers that affect their organization and social relations. To address these gaps, this research takes Beirut's (Lebanon) informal water system, and has three main objectives: 1) To analyze affordability disparities of two communities of different socio-economic levels by drawing upon different water affordability frameworks from the literature, 2) to assess the sustainability of informal water systems by analyzing the embedded energy of informal water systems and quantifying energy use and carbon emission differences between formal and informal water systems, 3) to identify and characterize key informal water tankers, and assess the drivers of their collaboration and competition through a social network analysis. Based on these three objectives, the dissertation has three core chapters: Chapter 2 focuses on the socio-economic impacts of informal water sources and their affordability disparities. Chapter 3 focuses on the environmental impacts of informal water sources, their energy-water nexus and carbon emissions. Chapter 4 focuses on a social network analysis of informal water tankers, and socio-cultural and environmental drivers that influence their cooperation and competition.

Case study selection

Beirut receives water from two main sources, shown on **Map 1**. The main source is a northern water treatment plant in Dbayeh, which supplies around 80% of the city's water. Another source is multiple groundwater wells in the south in Naameh area. Water from these locations is usually pumped to different reservoirs in Beirut for storage before delivery. The reservoirs cannot supply water on a 24/7 basis, so they pump water every 48 hours. Thus, residents receive water for a continuous period of around 3 hours per day in the summer and around 7 hours per day in the winter. To cope with the intermittence, residents in Beirut use various strategies and sources including pumping water from private wells, tanker trucks, and bottled water, as shown in **Figure 1.** For freshwater, people commonly maintain on-site storage in underground and roof reservoirs to capture intermittent piped water from the municipal water supply. The piped water is first sent to underground tanks, which is usually a large reservoir shared by building residents (ranging from 10 m^3 to 80 m^3). Once the building reservoir is full, the water is then pumped to individual smaller roof tanks assigned to each apartment or household. When both underground and roof reservoirs empty, buildings and households seek other water sources, either pumping water from private wells (sometimes with additional treatment using reverse osmosis - RO) or buying water from water tanker trucks that deliver water from wells located at the outskirts of the city. For potable needs, people rely mostly on bottled water, mainly because of distrust in the quality of delivered water (Zawahri et al., 2011). Bottled water companies usually draw water from the Lebanese Mountains where they pump and treat the water, and then fill the bottles for delivery. The bottles are then transported either directly to household or to local markets through regional delivery trucks.

Map 1 - Schematic water distribution system in Beirut, Lebanon.

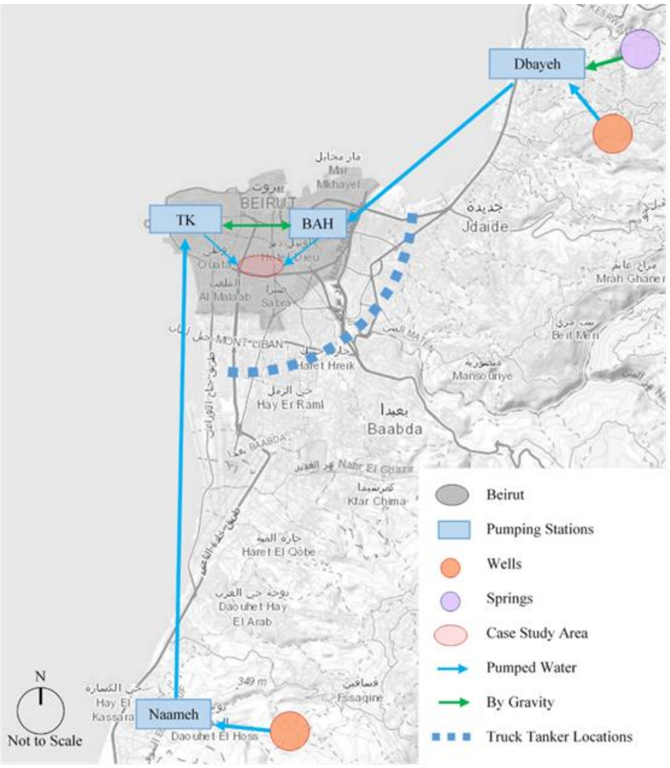
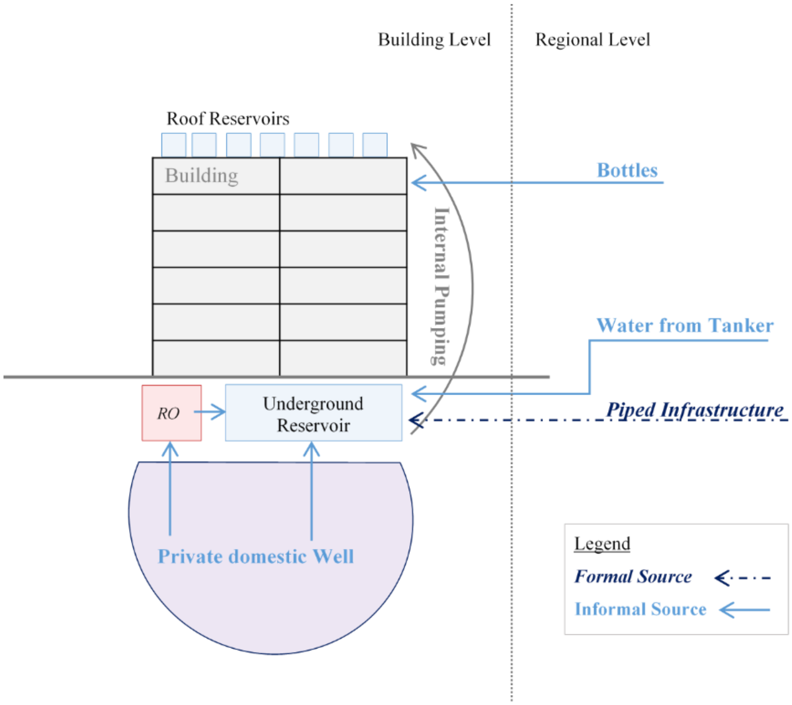


Figure 1 - Formal and Informal supply systems.



The selected case study area includes two communities of different socio-economic levels: Aicha Bakkar consists of lower income households, and Verdun of higher income households, as shown in **Map 2**. Chapter 2 compares water affordability for these two communities. Chapter 3 does not distinguish between the communities and analyzes the energy requirement of the entire case study area, because both communities are in the same water zone. This means they receive the same water volume, follow the same intermittent piped water delivery schedule and follow the same pumping schedule. So they have similar water and energy requirements.

Map 2 - Case study area: Aicha Bakkar and Verdun Communities.

Contributions

Methodologically, we contribute to three fields of water system research, including: water affordability, the energy-water nexus, and Social Network Analysis (SNA). Water affordability frameworks tend to focus on the cost of accessing piped drinking water (WHO/UNICEF JMP 2017). We contribute to the field by taking into account added costs of multiple informal water sources and by measuring affordability disparities of different income communities. Meanwhile, the field of water-energy nexus has mostly focused on the different environmental dimensions of energy use within formal piped infrastructure water systems (Spang et al 2020). We contribute and expand the field by considering the energy use and carbon emissions of informal water sources. Finally, SNA method is typically used to study patterns of social connections among stakeholders of formal institutions and organizations and aspects of their collaboration (Bodin et al 2020; Garcia, et al 2019). We advance the field by taking the example of an informal network and by analyzing simultaneous collaboration and competition among informal water tankers.

Within the literature on informal systems, we move away from the early dualistic approach of informality and show the inter-connection between formal and informal water systems. The formal piped infrastructure and informal sources together provide a holistic service, formal systems tend to be more affordable and informal sources tend to provide the needed volumes and reliability. Our case study shows the need for informal sources by different communities, and not only the urban poor. Informal water systems are flexible and capable of delivering the needed volumes to communities. However, we are critical when referring to them as resilient (Revell, 2010) as we also analyze their socio-economic and environmental impacts and drivers behind their organization.

Theoretically, we contribute to the fields of informality, political ecology, and water justice. Political ecology and water justice are often concerned with how formal piped systems tend to be anchored in social-ecological interdependencies where stakeholders, influenced by their political, economic and cultural interests, affect the way they manage water systems (McGinnis and Ostrom, 2014; Ingold et al 2018; Mancilla Garcia et al 2019). These interdependencies can often lead to uneven impacts by both enabling and disabling social and environmental conditions of communities for example by improving the environmental qualities for some communities while leading to disproportionate environmental deterioration for others (Swyngedouw, et al 2002; Swyngedouw 2009). While Political ecology and water usually focus on formal piped infrastructure; our research redirects the conversation towards informal water systems. We assess how different communities are situated differently in this informal waterscape by highlighting the disproportionate access and affordability disparities of lower income communities to informal water sources. We also focus on informal water tankers and identify the hidden socio-cultural and environmental drivers that indirectly influence the way they are managing water sources and indirectly controlling water access.

Organization of dissertation

Each chapter is summarized below including its main topics, main research question, applied methods, and major findings.

Chapter 2 focuses on the socio-economic impacts of informal water sources (tanker trucks, bottled water, and local wells) by examining their water affordability and disparities on two communities of different socioeconomic status in Beirut, Lebanon. The chapter explores how accessing multiple (formal and informal) water sources affects water affordability for communities with differing socioeconomic status. To measure affordability disparities of informal sources, two types of affordability frameworks are combined: those that evaluate cost and affordability of multiple water sources and activities, and those that capture water affordability of different income groups with a focus on lower income communities. The chapter accounts for the total cost of water services (from the piped infrastructure and additional cost of informal sources from tanker trucks, bottled water, and local wells), and divides these costs by the median incomes of high- and low-income communities. To measure levels of water (un)affordability for both communities, the cost-to-income ratios are then compared to three affordability thresholds of 3%, 5% and 10%. The chapter highlights water affordability disparities between both communities, differences in coping behaviors, and the scale of informal water costs relative to the formal water sector.

Chapter 3 focuses on the environmental impact of informal sources by comparing the energy-water nexus of informal water sources with piped infrastructure, using a Beirut neighborhood as a case study. The chapter examines the extent that energy use and carbon emissions vary between formal and informal water systems. This chapter compares energy use and carbon emissions per cubic meter and per capita for formal and informal water sources. Energy use and carbon emissions are calculated for three delivery stages per source including pumping, treatment and distribution. The chapter highlights the higher energy and carbon intensity of informal sources relative to the formal water system, and shows the importance of previously hidden impacts, such as from domestic water pumps that pump water between buildings' lower and upper reservoirs.

Chapter 4 focuses on analyzing the organization of the informal water tankers. The chapter examines who are the most influential informal water tankers in Beirut, and what drives them to cooperate and to compete. The chapter uses a social network analysis approach to study the network of informal water tankers. It develops the network's descriptive analysis at macro, meso and micro levels and presents its Exponential Random Graph Models (ERGMs). The main findings show that competition and cooperation among stakeholders are indirectly influenced by socio-cultural and environmental drivers: religion and years in the market, and that their relations also depend on the type of information that is being exchanged. Cooperation happens among Christian stakeholders that have been in the market longer and is based on sharing nonessential information (related to service quality and truck maintenance). Competition occurs over market price and service territories. Competitors tend to be more religiously diverse and to have entered the market more recently. Their entry also coincides with recent droughts in Lebanon. These droughts have increased household water intermittence and insecurity, and so expanded the demand for informal water tankers, suggesting a local effect of climate change.

References

Ahlers, R., Cleaver, F., Rusca, M., and Schwartz, K. (2014). Informal space in the urban waterscape: Disaggregation and co-production of water services. *Water Alternatives*. 7(1): 1-14.

AlSayyad, N. (2004). Urban informality as a “new” way of life. *Urban Informality: Transnational Perspectives from the Middle East, Latin America, and South Asia*, 7-30.

Alameddine, I., Tarhini, R., & El-Fadel, M. (2018). Household economic burden from seawater intrusion in coastal urban areas. *Water International*, *43*(2), 217–236.

Amit, R. K., & Sasidharan, S. (2019). Measuring affordability of access to clean water: A coping cost approach. *Resources, Conservation and Recycling*, *141*, 410–417.

Bakker, K. J. (2003). A political ecology of water privatization. *Studies in Political economy*, 70(1), 35-58.

Balazs, C. L., & Lubell, M. (2014). Social learning in an environmental justice context: a case study of integrated regional water management. *Water Policy*, 16(S2), 97-120.

Balazs, C. L., & Ray, I. (2014). The drinking water disparities framework: on the origins and persistence of inequities in exposure. *American Journal of Public Health*, 104(4), 603-611.

Baquero, O. F., Gallego-Ayala, J., Giné-Garriga, R., de Palencia, A. J.-Fernández., & Pérez-Foguet, A. (2017). The Influence of the Human Rights to Water and Sanitation Normative Content in Measuring the Level of Service. *Social Indicators Research*, *133*(2), 763–786.

Bodin, Ö., Mancilla García, M., & Robins, G. (2020). Reconciling conflict and cooperation in environmental governance: A social network perspective. *Annual Review of Environment and Resources*, *45*, 471-495.

Christian-Smith, J., Balazs, C., Heberger, M., & Longley, K. (2013). Assessing water affordability. *A pilot study in two regions of California, Pacific Institute.*

Cheng, D. (2014). The Persistence of Informality: Small-Scale Water Providers in Manila's Post-Privatisation Era. *Water Alternatives*, *7*(1).

Constantine, K., Massoud, M., Alameddine, I., & El-Fadel, M. (2017). The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of Environmental Management*, *188*, 85-94.

Davis, J. (2004). Corruption in public service delivery: experience from South Asia's water and sanitation sector. *World development*, *32*(1), 53-71.

El-Fadel, M., Maroun, R., Semerjian, L., & Harajli, H. (2003). A health-based socio-economic assessment of drinking water quality: The case of Lebanon. *Management of Environmental Quality: An International Journal*, *14*(3), 353–368.

Farrelly, M. A. & Brown R. R. (2014) Making the implicit, explicit: time for renegotiating the urban water supply hydrosocial contract? *Urban Water Journal,* 11, 392-404.

Mancilla García, M. M., Hileman, J., & Bodin, Ö. (2019). Collaboration and conflict in complex water governance systems across a development gradient. *Ecology and Society*, *24*(3).

Hanak, E. *et al* (2011). *Managing California's Water from Conflict to Reconciliation*. Public Policy Institute of California.

Hart, K. (1973). Informal income opportunities and urban employment in Ghana. *The journal of modern African studies*, 11(01), 61-89.

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, *4*(5), 390-405.

Ingold, K., Driessen, P. P. J., Runhaar, H. A. C., & Widmer, A. (2018). On the Necessity of Connectivity: Linking Key Characteristics of Environmental Problems with Governance Modes. *Journal of Environmental Planning and Management*, online.

Jepson, W., & Vandewalle, E. (2016). Household water insecurity in the global north: a study of rural and periurban settlements on the Texas–Mexico Border. *The Professional Geographer*, *68*(1), 66-81.

Kjellén, M., & McGranahan, G. (2006). *Informal water vendors and the urban poor* (pp. 978-1). London: International Institute for Environment and Development.

Komarulzaman, A. (2017). *Water affordability, water quality and their consequences for health and education in Indonesia* (Doctoral dissertation, Radboud Repository of the Radboud University, Nijmegen, the Netherlands).

Kooy, M. (2014). Developing Informality: The Production of Jakarta's Urban Waterscape. *Water Alternatives*, 7(1).

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., ... & Ward, P. J. (2016). The world’s road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific reports*, 6, 38495.

Liddle, E. S., Mager, S. M., and Nel, E. L. (2016). The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *The Geographical Journal*, 182(1), 85–96.

London, J. K., Fencl, A. L., Watterson, S., Choueiri, Y., Seaton, P., Jarin, J., ... & Bailey, C. (2021). Disadvantaged Unincorporated Communities and the Struggle for Water Justice in California. *Water Alternatives*, *14*(2), 520-545.

Lubell, M. (2015). Collaborative partnerships in complex institutional systems. *Current Opinion in Environmental Sustainability*, 12, 41-47.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science advances*, 2(2), e1500323.

McGinnis, M. D., & Ostrom, E. (2014). Social-Ecological System Framework: Initial Changes and Continuing Challenges. *Ecology and Society*, *19*(2), 30.

Muller, M. (2012) Water management institutions for more resilient societies. *Civil Engineering special Issue*, 125, 33-39

Misra, K. (2014). From Formal-Informal to Emergent Formalisation: Fluidities in the Production of Urban Waterscapes. *Water Alternatives*, 7(1).

Moore, E., Matalon, E., Pacific Institute (Oakland, Calif.), Community Water Center, Clean Water Fund (Washington, D. C.), & California Rural Legal Assistance Foundation. (2011). *The human* *costs of nitrate-contaminated drinking water in the San Joaquin Valley*. Pacific Institute. http://www.pacinst.org/reports/nitrate_contamination/nitrate_contamination.pdf

Moretto, L., 2005, December. Urban governance and informal water supply systems: different guiding principles amongst multilateral organisations. In *Conference on the Human Dimension of Global Environmental Governance*, Berlin (pp. 2-3).

Nastiti, A., Sudradjat, A., Geerling, G. W., Smits, A. J. M., Roosmini, D., & Muntalif, B. S. (2017). The effect of physical accessibility and service level of water supply on economic accessibility: A case study of Bandung City, Indonesia. *Water International*, *42*(7), 831–851.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., & Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, *44*, 358–366.

Pattanayak, S. K., Yang, J.-C., Whittington, D., & Bal Kumar, K. C. (2005). Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal: COPING WITH UNRELIABLE PUBLIC WATER SUPPLIES. *Water Resources Research*, *41*(2).

Peloso, M., & Morinville, C. (2014). 'Chasing for Water': Everyday Practices of Water Access in Peri-Urban Ashaiman, Ghana. *Water Alternatives*, 7(1).

Pickett, S. T., Cadenasso, M. L., & Grove, J. M. (2004). Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landscape and urban planning*, *69*(4), 369-384.

Ranganathan, M. (2014). 'Mafias' in the waterscape: Urban informality and everyday public authority in Bangalore. *Water Alternatives*, 7(1).

Revell, K. (2010, September). Working with informality: increasing resilience in cities of the Global South. In *46th ISOCARP Congress* (pp. 1-13).

Rogers, P., and Hall, W. (2003). Effective Water governance. In *GWP Technical Committee Background Papers No. 7*. Global Water Partnership, Stockholm.

Roy, A. (2005). Urban Informality: Toward and Epistemology of Planning. *Journal of the American Planning Aoosication*, 71(2), 147-158.

Roy, A. (2009). Strangely familiar: Planning and the worlds of insurgence and informality. *Planning Theory*, *8*(1), 7-11.

Schwartz, K., Tutusaus Luque, M., Rusca, M., & Ahlers, R. (2015). (In) formality: the meshwork of water service provisioning. *Wiley Interdisciplinary Reviews: Water*, *2*(1), 31-36.

Spang, E. S., Manzor, S., & Loge, F. J. (2020). The cost-effectiveness of energy savings through water conservation: a utility-scale assessment. *Environmental Research Letters*, *15*(11), 114031.

Swyngedouw, E. (2009). The political economy and political ecology of the hydro-social cycle. *Journal of contemporary water research & education*, *142*(1), 56-60.

Swyngedouw, E., Kaika, M., & Castro, E. (2002). Urban water: a political-ecology perspective. *Built Environment (1978-)*, 124-137.

Teodoro, M. P. (2018). Measuring Household Affordability for Water and Sewer Utilities: Measuring Household Affordability for Water and Sewer Utilities. *Journal - American Water Works Association*, *110*(1), 13–24.

Thompson, J. et al., (2001). *Drawers of water II: 30 years of change in domestic water use & environmental health in east Africa. Summary* (Vol. 3). International Institute for Environment and Development.

Trærup, S. (2012). Informal networks and resilience to climate change impacts: A collective approach to index insurance. Global Environmental Change, 1 (22), 255-267.

Walter, C. T., Kooy, M., & Prabaharyaka, I. (2017). The role of bottled drinking water in achieving SDG 6.1: An analysis of affordability and equity from Jakarta, Indonesia. *Journal of Water, Sanitation and Hygiene for Development*, 7(4), 642-650.

WHO/UNICEF JMP. (2017). *Progress on drinking water, sanitation and hygiene: 2017update and SDG baselines* (Geneva) Online: http://www.who.int/iris/handle/10665/258617

Wutich, A., Beresford, M., & Carvajal, C. (2016). Can informal water vendors deliver on the promise of a human right to water? Results from Cochabamba, Bolivia. *World Development*, *79*, 14-24.

Young, S. L., Collins, S. M., Boateng, G. O., Neilands, T. B., Jamaluddine, Z., Miller, J. D., ... & Schuster, R. C. (2019). Development and validation protocol for an instrument to measure household water insecurity across cultures and ecologies: the Household Water InSecurity Experiences (HWISE) Scale. *BMJ open*, 9(1), bmjopen-2018.

Zawahri, N., Sowers, J., & Weinthal, E. (2011). The Politics of Assessment: Water and Sanitation MDGs in the Middle East: Water and Sanitation MDGs in the Middle East. *Development and Change*, *42*(5), 1153–1178.

Chapter 2: Affordability of Informal Water Systems - Comparing Water Affordability of Two Communities in Beirut, Lebanon[1]

Abstract

Achieving affordable and equitable water access for all remains a challenge worldwide. In areas with water shortages, individuals and communities change their behavior to accommodate the absence or unreliability of water, and pay added costs for alternative informally acquired water (such as from tanker trucks, bottles or wells). Water affordability studies rarely consider added costs from informal water sources and it is unclear how communities of different socio-economic levels cope with these costs. To analyze water affordability disparities from informal sources, this study compares water costs and affordability in two communities of difference socioeconomic status in Beirut, Lebanon. The study highlights water cost implications of informal sources and evaluates overall affordability disparities.

In both communities, informal water sources are around 88% of the total cost of water, but provide only 23% of average water use volume. Households pay roughly 10 times more for informal sources than for water delivered through the public water infrastructure system. Water is rather unaffordable for the entire sample population with an affordability ratio of 6% (average water cost is 6% of median income). Comparing both income communities shows stark disparities. Although the lower income community has lower total water costs, its residents access less affordable water, paying 2.2 times more of their income for water. The per household analysis shows more than half of these residents (55% of households) spend more than 5% of their income on water.

Lower income communities change consumption behavior and schedule their highly intensive water activities (i.e., washing clothes) when the municipal water is supplied (since it is the cheapest water). Coping costs, from increased pumping and treatment, tends to be higher in higher income communities because they can access more expensive treatment technologies.

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[1] All costs in this study are in $US.

Introduction and Literature Review

The affordability of water supplies has been an issue for engineers and planners for centuries. Today's literature provides no single standardized definition of water affordability, nor a common framework to calculate it. Different affordability frameworks capture water quality, availability, and overall equity of water systems by using components of volume, cost, household expenditure, and household income. This introduction highlights developing notions of water affordability and identifies some major components of affordability frameworks. While some frameworks evaluate the cost and affordability of accessing multiple water sources and activities, others capture water affordability of different income groups with a focus on lower income communities. This study combines these two lines of frameworks: we consider costs of accessing multiple water sources (formal piped infrastructure and informal sources such as tankers, wells and bottles) for two communities of different socioeconomic levels. This allows us to analyze water affordability disparities of accessing multiple sources. The introduction ends with the overall study's focus, research question and framework.

Early use of water affordability

A well-documented and popular use of the concept of water affordability is the United Nations' General Comment No. 15 on the right to water, in 2002 (CESCR, 2003). The General Comment on the human right to water included three main characteristics of availability, quality, and accessibility. The latter included sub-elements of physical, economic, non-discrimination, and information accessibilities. Within these, economic accessibility mentioned the term affordability by stating that water facilities and services must be affordable for all and that the direct and indirect cost of water must not reduce a person's access to other rights (UN, 2002; Goddard, 2019, p. 19). This statement lacked a more direct definition of the term affordability and lacked methods to calculate and achieve affordable water systems.

Ten years later, the United Nations' Sustainable Development Goal (SDG) #6, focusing on water and sanitation, included targets and indicators to ensure availability and sustainable management of water and sanitation for all (UN, 2020). To monitor and operationalize these SDG targets, the WHO and UNICEF established the Joint Monitoring Programme (JMP) to measure access to drinking water (Zawahri et al., 2011; WHO/UNICEF JMP 2017). The JMP assesses access and coverage rates by solely looking at the sources and technologies that deliver "improved" drinking water and sanitation. Improved, refers to having connections through piped household water, protected wells, protected springs, and rainwater collection (UNICEF & WHO, 2006; Komarulzaman, 2017, p.13; Walter et al., 2017). The JMP's focus on measuring whether households have a physical connection to a water system or a protected source was insufficient as it did not capture the quality, availability, and affordability of water supply (Zawahri et al., 2011; Onda et al., 2012; Satterthwaite, 2016; Walter et al., 2017; Nastiti et al., 2017).

To capture water quality, availability, and overall equity of water systems, affordability frameworks emerged and included different components of volume, cost, household expenditure, and income, as developed below.

Water affordability frameworks and components

Affordability frameworks generally look at the cost of accessing water sources relative to the economic resources of households or total household expenditure (Sawkins & Dickie, 2005; Mack & Wrase, 2017; Goddard, 2019, p. 19). These ratios are then compared to a threshold to indicate achievement of relatively affordable water based on income or wealth (Hutton 2012). Some studies adopt a macro analysis approach, using average consumption and income levels of entire study population. Other studies adopt a micro and more detailed analysis approach, using individual household consumption volumes, costs, expenditures, and incomes (García-Valiñas et al., 2010a; Martins et al., 2019; Sawkins et al., 2005; Komarulzaman, 2017, p.13), and choosing a specific approach can be critical in the way we understand

and analyze affordability (Meehan et al 2020). The paragraphs below discuss each of these components and highlight elements considered by this study.

Volume

Both the right to water definition and the JMP focus on people's access to drinking water, which is usually less than 10% of household total water use (Clasen et al., 2008). More advanced frameworks include drinking and freshwater needs such as hygiene, washing, and cleaning (Nastiti et al., 2017). For example, White et al., (2002), in the 1970's, divides domestic water into categories of: (i) *consumption* (drinking and cooking) (ii) *hygiene* (bathing, washing and cleaning) and (iii) *amenities* (watering lawns, car-washing and other non-essential tasks). Similarly, Gleick (1996) states that people have four water needs: drinking, hygiene, sanitation, and household (for the preparation of food), while continuing to allocate sufficient water for the protection of natural ecosystems. Affordability studies are diverse in how they account for water volumes as shown in **Table 5** below.

Table 5 – Overview of affordability studies and variation in water consumption levels

	Affordability based on different volumes	**Location**	**Reference**
Higher Income Areas + Piped access	Average Water Consumption among all households	Portugal USA	Martins et al., (2019) Mack and Wrase (2017)
	Average Household Basic Water Needs	Spain Belgium	García-Valiñas et al., (2010a, b) Vanhille et al., (2018)
	Individual Household Water Consumption	Great Britain Washington D.C.	Sawkins & Dickie (2005) Teodoro (2005)
Lower and Middle Income Areas + Piped access	Average Household Basic Water Needs	Tunisia Developing countries generally USA	Sebri (2015) Smets (2009) Teodoro (2018)
Lower and Middle Income Areas + Access from Multiple Sources	Average Household Basic Water Needs	Indonesia	Komarulzaman (2017, p. 13)
	Water Activities Needs: Drinking,	Nepal Indonesia	Pattanayak et al., (2005) Nastiti et al., (2017)

	Cooking, Bathing and Washing		
Low Income Areas + Access To Multiple Sources	Water Activities divided as: Consumption, Hygiene, Amenities and Productive uses	East Africa	Thompson et al., (2001)

Whether focusing on higher or lower income areas, or assessing water access through centralized water pipes or multiple water sources, studies have looked at overall water use levels in different ways as shown in **Table 5**. However, identifying volumes can be controversial (Goddard, 2019, p.19), and each method has strengths and weaknesses:

- Average water consumption among all households might either include over-consumption of water for amenities (such as irrigation and swimming pools) or under-consumption in “water-poor” households (García-Valiñas et al., 2010b; Komarulzaman, 2017, p.13; Vanhille, et al., 2018; Martins et al., 2019).
- Basic water needs focuses on the amount of water for fundamental household needs (usually drinking, cooking, sanitation). However, there isn’t a consensus defining basic needs or need volumes, which range from 15 to 100 liters per person per day (Thompson et al., 2001; Gleick, 1996; García-Valiñas et al, 2010b; Sebri, 2015; Komarulzaman, 2017, p.13).
- Individual water use levels require refined census data that capture exact use levels of households (Teodoro, 2018), which is often not readily available (Zawahri et al., 2011; Goddard, 2019, p.19).

This study analyzes water affordability for all water needs at the household level (including potable uses and freshwater needs such as bathing and washing). As discussed above, basic water needs do not include additional household water needs, and refined census data on individual water consumption, that usually measure water affordability related to multiple needs, is unavailable in Lebanon. So this study considers overall household freshwater and potable needs by looking at the volume of multiple water sources delivered for different needs (e.g. formal piped infrastructure, water tankers and wells for freshwater needs, and bottles for potable and cooking needs).

Cost

Affordability frameworks that usually assess centralized piped systems tend to consider only the cost of water bills (Mack & Wrase, 2017; García-Valiñas, et al., 2010a; Vanhille, et al., 2018; Goedemé and Vanhille, 2018). However, in much of the world, piped water systems suffer from intermittence, leading to the delivery of unreliable and often unsafe water (Zawahri et al., 2011, Nastiti et al., 2017). So people often use additional alternative water sources (Pattanayak et al., 2005; Zawahri et al., 2011; Nganyanyuka et al., 2014; Nastiti et al., 2017; Amit and Sasidharan, 2019). Many frameworks account for the cost of multiple sources and their coping behavior as summarized in the **Table 6**.

Table 6 – Affordability studies and variation in added costs computation.

Costs considered	**Focus**	**Location**	**Reference**
Cost of Alternative Drinking Water Sources	Replacement cost of vended and bottled water Expenditures on vended and bottled water Absolute affordability of packaged drinking water.	California California Indonesia	Christian-Smith et al., (2013) Moore et al., (2011) Walter et al., (2017)
Cost of Alternative Water Sources	Expenditures on multiple sources Shadow prices for alternative water sources	Indonesia Indonesia	Nastiti et al., (2017) Komarulzaman (2017)
Cost of Water and Sewer	Cost of water and sewer services in relation to other essential costs.	USA	Teodoro (2018)
Cost of coping behavior	Full financial and non-financial costs of water Coping cost of collecting, pumping, treating, storing, and purchasing. Coping costs of collecting, pumping, treating, storing, and purchasing canned water. Cost of distance and time travelled to reach a water point Descriptive and evaluative framework to capture the complex mix sources.	NA Nepal India Mozambique and Nicaragua Dar es Salaam	Hutton (2012) Pattanayak et al., (2005) Amit and Sasidharan (2019) Baquero et al., (2017) Nganyanyuka et al., (2014)

Some studies calculate the cost of alternative sources by focusing only on drinking water. For example, Christian-Smith et al., (2013) and Moore et al., (2011) analyze costs of vended and bottled water in California; and Watler et al., (2017) assesses volumes of refill water in Indonesia. Other studies move beyond drinking water and include piped water, bottled water, groundwater, spring, and taps (Komarulzaman, 2017, p.13; Nastiti et al., 2017), or the cost of both water and sewer services and the ability of individuals to pay for those services while still being able to afford other essential costs such as housing, food, health care, and energy (Teodoro, 2018). Others focus on costs of behaviors that emerge as people cope with the absence of piped water supplies. For example, Hutton (2012) develops four affordability methods that include connection costs, and other costs related to storage, treatment or water hauling, and payment time; Amit and Sasidharan (2019) and Pattanayak et al., (2005) calculate costs of collecting, pumping, treating, storing, and purchasing canned water in Nepal and India. Baquero et al., (2017) considers the distance and time travelled to reach a water supply in Mozambique and Nicaragua. Nganyanyuka et al., (2014) develop a more descriptive and evaluative framework to capture the complex mix of sources, uses, and intermediaries in planned and unplanned settings in Dar es Salaam.

Since Beirut experiences water supply intermittence from the formal piped-infrastructure, household tend to resort to alternative water sources to satisfy their daily needs. Therefore, the current study accounts for the cost of all formal piped infrastructure and informal water sources including subscription fees to the formal piped system, cost of water bottles, tankers and wells. Moreover, as people tend to change their behavior to cope with insufficient water availability, the current study also accounts for two main coping costs related to pumping (from private wells and internally at a building’s level) and treatment (through the use of domestic reverse osmosis units).

Income and Expenditure

Affordability methods usually measure the cost of water sources as a proportion of household income or expenditures. As summarized in **Table 7**, below, affordability studies have been diverse in how they address income.

Table 7 – Affordability studies and variation in income and expenditure levels.

Income Characteristics	**Study Aspect**	**Location**	**Reference**
Water Expenditure	Water expenditure for four income groups. Water costs for different income groups. Coping costs for different income groups.	Indonesia Nepal Mozambique and Nicaragua	Nastiti et al., (2017) Pattanayak et al., (2005) Amit and Sasidharan (2019)
Multiple Income Groups	Median incomes of different income group blocks. Monthly income spent on refill water for 5 income groups.	California Indonesia	Christina-Smith et al., (2013) Walter et al., (2017)
Ethnic Groups	The median income of different racial/ethnic groups	USA	Mack & Wrase (2017)
Lower Income	20th percentile of household from the lower boundary of the middle class. Self-reported household income for low-income households.	USA California	Teodoro (2018) Moore et al., (2001)
Disposable Income	Household income spent on basic water consumption. The mean percentage of net weekly household income spent on water and sewerage. Household income divided by the expenditure spent on water services	Tunisia Great Britain Indonesia	Sebri (2015) Sawkins & Dickie (2005) Komarulzaman (2017, p.13)

Studies have compared different (higher- and lower-) income groups by looking at their water expenditure differences (Nastiti et al., 2017; Pattanayak et al., 2005; Amit and Sasidharan, 2019), their median incomes (Christina-Smith et al., 2013), or their average incomes (Walter et al., 2017). Some studies consider the median income of different racial and ethnic groups (Mack & Wrase, 2017). Other studies focus solely on lower income communities (Moore et al., 2001; Teodoro, 2018). And a last group investigated the disposable income available to be spent on water (Sawkins & Dickie, 2005: Sebri, 2015; Komarulzaman, 2017, p.13).

Affordability frameworks can be divided into income-based measures and expenditure-based measures. Former methods compare water expenditures relative to household income; whereas latter methods compare water expenditures to total household expenditures (Sawkins & Dickie, 2005; Mack & Wrase 2017). While household income data is generally easier to collect, it may obscure the real impact of water expenditures for three main reasons (Teodoro, 2005; García-Valiñas, 2010b; Mack & Wrase, 2017; Goddard, 2019, p.19): First, gross income can overestimate household income availability since not all income is available to pay for water (Goddard, 2019, p. 19). Alternatively, gross income may underestimate income availability when lower income households rely on multiple or variable income sources such as seasonal employment (Martins et al., 2019). Finally, in some cases, income data tend to be inaccurate or unavailable, especially in developing countries (Pattanayak et al., 2005; Nastiti et al., 2017; Amit and Sasidharan, 2019; Martins et al., 2019).

For our study, we are interested in comparing water affordability for high and low-income communities. Thus, from **Table 7**, we follow examples that have examined different income groups. We take median income levels of two high and low-income communities in Beirut and develop their detailed household income analysis. Moreover, governmental data on household expenditure was not reliable in Lebanon, so we adopt an income-based approach by computing income levels, collected from the study’s survey.

Threshold

Once ratios between water costs and household income (or expenditure) are computed, their results are compared to a threshold, that classifies whether the household is considered to have affordable water or not. There isn't a consensus on affordability thresholds yet, and they can range from 1.4% to 10%, as indicated in **Table 8**.

Table 8 – Affordability thresholds of water cost as a percent of income from various studies (Based on Goddard, 2019).

Affordability thresholds	Water Cost	Income definition	Reference	Location
1.4%	Drinking Water	DI	Vanhille, et al., (2018)	Belgium
2%	Drinking Water	MHI and income of group blocks	Christian-Smith et al., (2013)	California
3%	Basic water consumption	DI	García-Valiñas et al., (2010a)	Spain
3%	Water and Sewage Services	DI	Sawkins & Dickie (2005)	Great Britain
3 – 5%	Basic water consumption	DI	Sebri (2015)	Tunisia
4%	Basic Water consumption	DI	Komarulzaman (2017)	Indonesia
4.5%	Basic water and sewer services	MHI	Mack & Wrase (2017)	USA
4.6%	Drinking Water	MHI	Moore et al., (2011)	California
5%	Infrastructure Cost	Household Budget Expenditure.	Banerjee and Morella, (2011)	Africa
10%	Drinking water and Wastewater	Income without taxes and other essential expenses.	Teodoro et al., (2018)	25 largest US cities

MHI= Median Household Income (overall income)
DI= Disposable Income (available income to spend on water only)

Thresholds differ depending on what counts as a cost (drinking water, or overall water) and how income is measured (disposable or gross income) (Smets, 2012; Hutton, 2012; Mack & Wrase 2017; Teodoro, 2018). Moreover, they vary across countries and international organizations. Smets (2012) looks at affordability thresholds of different countries that have either compared costs of water, or cost of water & sanitation, with either individual household, or median household disposable income. The ratios generally range from 2% to 6% as shown in **Table 9**.

Table 9 – Affordability thresholds in different countries (based on Smets, 2012).

Threshold	**Countries**
2%	Lithuania; United States
3%	Northern Ireland; France; Argentina
4%	Venezuela; Indonesia; Mongolia
5%	Chile; Kenya
6%	Mongolia

Hutton (2012) points out that international agencies’ affordability thresholds usually range from 3% to 5%. **Table 8** and **Table 9** show that most thresholds used in other case studies and countries also fall between 3% and 5%. Hence, this study considers water affordability thresholds of 3% and 5%. In addition, since we are also interested in investigating whether households in Beirut face excessive water unaffordability, we include a 10% threshold, following the highest percentage from **Table 8**. In sum, the study compares affordability ratios of both communities using the thresholds of 3%, 5% and 10%.

Focus and Research Question

The affordability frameworks discussed above can be divided in two: those that evaluate the cost and affordability of accessing multiple water sources and activities, and others that capture water affordability of different income groups with a focus on lower income communities. This study combines these two lines of frameworks. We assess water affordability of Lebanese households by comparing costs of formal and informal water sources with median income levels of two communities (high and low-income), and develop a detailed per household income analysis. The study seeks to examine how accessing multiple (formal and informal) water sources affects water affordability for communities with differing socioeconomic status. The study accounts for water demand volumes, including temporal, and seasonal variation. It calculates the cost of multiple water sources and their associated coping costs (of technology –treatment and pumping- and behavioral changes) by identifying the total water use, temporal delivery of sources (frequency of delivery), and water cost by water source. The combination of this data reveals the total cost of water services for households in these Lebanese communities. These costs are divided by the median incomes of high- and low-income communities. To measure levels of water affordability for both communities, the cost-to-income ratios are then compared to three affordability thresholds of 3%, 5% and

10%. The results highlight three main findings: informal water cost implications, affordability ratios of both income groups, and overall affordability disparities.

Framework: informality and socio-economic impacts

Studies on informal water supplies are diverse, and most analyze socio-political drivers of informal water supplies without measuring socio-economic impacts of informal water sources on communities. **Table 10** summarizes the literature on informal water systems focusing on socio-political drivers, dividing them into public administration drivers that lead to the development of informality, and social relations affecting informal water supplies.

Table 10 - Drivers of Informality.

Drivers of informality	Focus	Location	Reference
Public Administration Drivers	Incapacity of newly independent colonies to manage water	Zambia	Liddle et al (2016)
	Governmental rationalities that produced unequal water access	Jakarta	Kooy (2014)
Social Relations	Meshwork of actors	Mozambique	Schwartz, (2015)
	Co-production of water provision	Mozambique	Ahlers et al. (2014)
	Water provision is a combination of people and infrastructure	Ghana	Peloso and Morinville (2014)
	Water systems are hydrosocial relations	Texas-Mexico Border	Jepson and Vandewalle (2016)

Liddle et al (2016) take the example of Zambia and Ndola and explain how newly independent colonies were ill equipped politically, socially, economically and administratively to develop and manage water resources. Kooy (2014) explains that roots of inequality in water access. In Jakarta accessing water is not related to water supply or distribution of technology/infrastructure but to the politics of water that are based on governmental decisions that secure water quantity and quality to communities depending on their class and race. Formal and informal systems are entangled in a meshwork of actors with their own authorities and ability to produce and reshape flows and practices (Schwartz, 2015). Ahlers et al. (2014) analyze how water provision involves daily negotiations that are co-produced among different stakeholders at multiple scales and dynamic social relations. Peloso and Morinville (2014) look at everyday informality which combines people and infrastructure as people become the infrastructure as they engage in multiple, repetitive actions that enable water access to those experiencing water shortages. Jepson and Vandewalle (2016) show how water disparities issues along Texas-Mexico border stem from complex interactions among institutions, organizations, and technologies.

In the field of water security, some studies show psychological and physical impacts of water shortages on lower income areas by focusing on indicators related psychology (worries about water), physical health, nutrition, livelihoods, household economy, and agriculture (Jepson and Vandewalle, 2016; Wutich et al., 2107; Jepson et al., 2017a, b; Young et al. 2019). Few studies focus on how informality affects communities and its socio-economic aspects. Our study addresses this gap and highlights affordability disparities by focusing on the economic impacts of informality of high and low- income communities. It divides the multiple water sources in two: formal piped infrastructure and informal water sources (delivered by water tankers, pumped from private wells, and delivered through bottles). This shows the magnitude of informal water source costs compared to overall water costs. The study also compares these costs for two income communities, and examines how different income groups cope with these added costs.

Case Study Area Selection

Selection of two communities

This study evaluates water affordability for two communities in Lebanon with differing incomes. We sought adjacent communities that have different urban typologies and different socio-economic and sectarian characteristics. However, since they are adjacent to each other, they share similar water profiles (i.e. have similar supply patterns from the piped infrastructure), as discussed further.

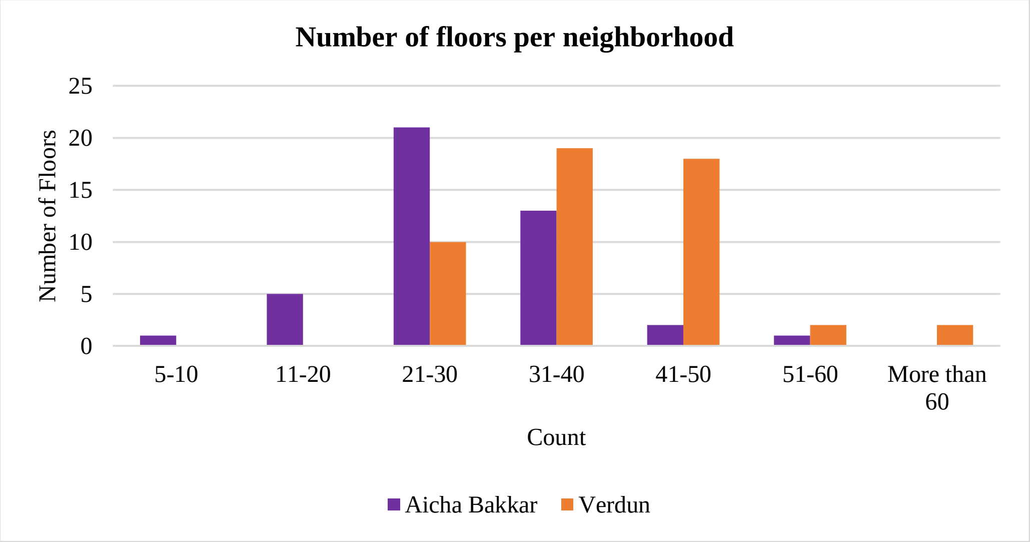
Urban and Social Characteristics

Census data do not exist in Lebanon, so the selection of the income groups was based on the researcher's local knowledge of the urban neighborhoods and cross-validated by local academicians and urban planners (such as the Urban Lab at the American University of Beirut). The selected case studies are adjacent communities in western Beirut: Aicha Bakkar (lower income) and Verdun (higher income), shown in **Map 3.**

Map 3 – Location of income communities.

Although the communities are adjacent, they have different urban typologies. Based on the surveyed buildings, Aicha Bakkar has shorter buildings, with 70% of buildings' height between 21 to 40 meters high and an average buildings' footprint of 220 m^2. Verdun has taller buildings, with 70% of buildings' height between 31 and 50 meters and an average buildings' footprint of 320 m^2. **Figure 2** shows the average number of floors per building for each community. This is also linked to the development period of each area. Aicha Bakkar's urban development, that started in the 1920s, was unplanned and evolved organically leading to a closely knit typology with smaller building footprints and streets. Whereas Verdun's development started 40 years later in the 1960s. The late development is related to a landownership dispute, of four main land parcels, which halted any land selling. Once the lands were foreclosed by the court, the municipality was able to subdivide the lands following a grid-like typology which leads to today's large homogenous-shaped lots and large buildings footprint (Zaatari, 2019). Both areas have socio-economic and sectarian differences. While the majority of residents in both areas share a similar religious background being Sunni Muslim, Aicha Bakkar is predominantly a low-middle income Sunni Muslim community while Verdun is an upper income relatively mixed community of Lebanese and Syrian Sunni Muslims, (Zaatari, 2019).

Figure 2 – Average number of floors per building for each community.

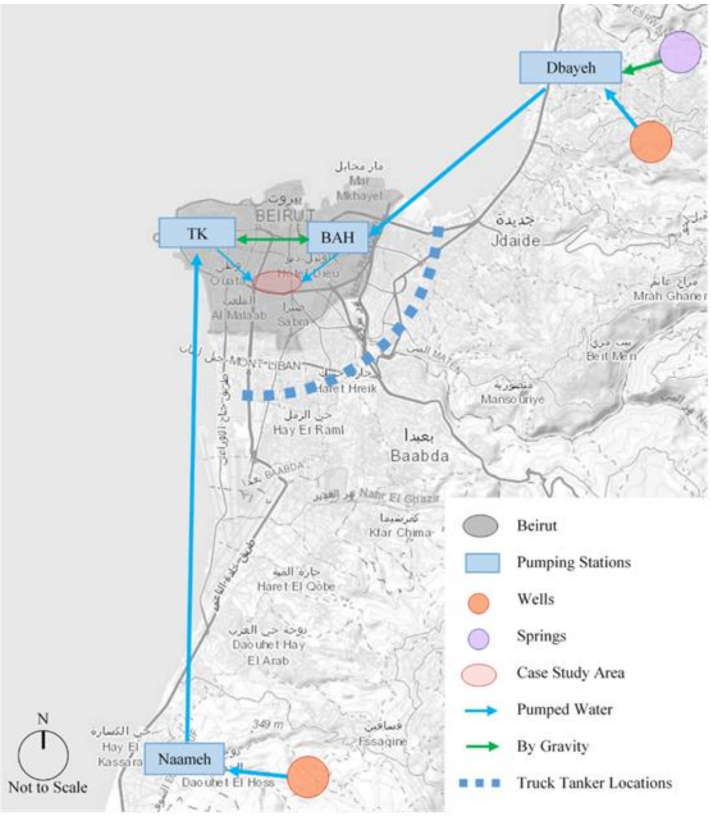


Water Distribution, Intermittence and Urban Coping Strategies

Beirut receives water from two main sources, shown on

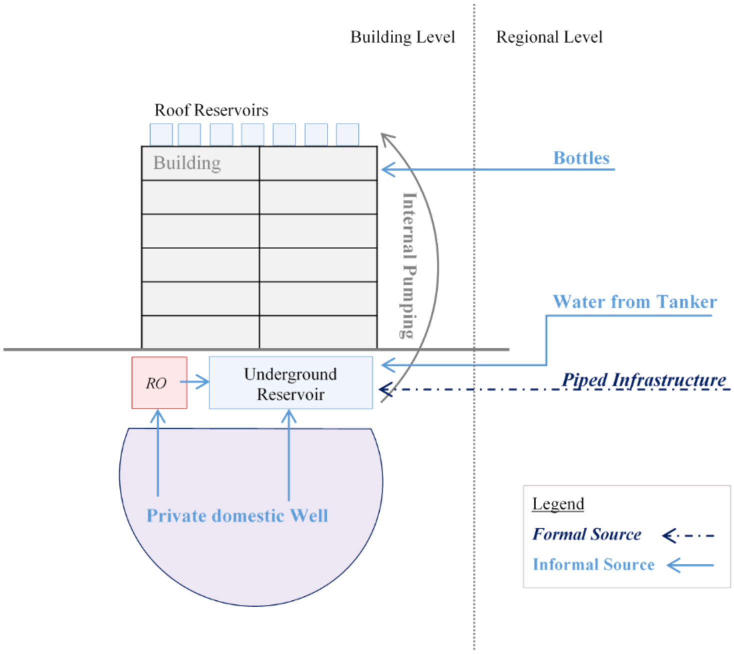
. The main source is a northern water treatment plant in Dbayeh, which supplies around 80% of the city's water. Another source is multiple groundwater wells in the southern Naameh area. Water from these locations is usually pumped to reservoirs in Beirut for storage before delivery. The reservoirs cannot supply water on a 24/7 basis, so they release water to different water zones every 48h hours. The two selected communities, Aicha Bakkar and Verdun, are in the same water zone, meaning they receive the same amount of water and follow the same intermittent piped water delivery schedule. They received around 16,000m^3 of water every 48h from two reservoirs, Burj Abi Haidar (BAH) and Tallet el Khayyat (TK).

Map 4 - Schematic water distribution system in Beirut, Lebanon.



To cope with the intermittence of the piped infrastructure, people in Beirut rely on various strategies at building and household scales. People rely mostly on bottled water mainly for drinking (and sometimes for cooking), because of lack of trust in the quality of delivered water (Haddad, 2002; Zawahri et al., 2011). Bottles are typically delivered directly to households. For freshwater, people commonly maintain on-site storage in underground and roof reservoirs to capture intermittent piped water. The formal piped water is first sent to underground tanks, usually a large reservoir shared by residents of a building. Once the large reservoir is full, the water is pumped to individual smaller roof reservoirs assigned to each apartment or household. When both underground and roof reservoirs empty, buildings and households seek other water sources, either pumping water from private wells (sometimes with additional treatment, such as reverse osmosis) or buying water from water tanker trucks businesses.

Figure 3 - Water supply at different scales: building and household scales.



Data Collection

Data on household water consumption and expenditures were collected by in-person household interviews in Aicha Bakkar and Verdun communities over a two months from October and November 2019. The interviews were conducted in multiple languages: the questions were mainly asked in Arabic and when necessary (especially when using some technical terms), the interviewer asked the questions in French and/or English. The answers were collected using the Survey123 phone application from ESRI ArcGIS. The questions followed an interview guide with four topic areas:

1. Urban typology questions focusing on the location and age of building, number of floors, and number of apartments.
2. Socio-economic questions on occupation, age, and educational level of household owners.
3. Water system questions on the volume of water deliveries by water source type, temporal delivery of sources (frequency of delivery), cost, scale of delivery (i.e., is water delivered for the building or the household), and seasonal variations.

4. Additional questions on residential water treatment information, such as: the use and cost of reverse osmosis treatment; storage capacity information including building level tank volumes and location; and residents' general perception of the formal and informal systems.

The interviews were completed with at least one adult from each surveyed household. All household owners were able to give reliable information on purchase of bottled drinking water. However, most did not know exact information on sources delivered at the building level, such as water delivered through utility pipes or the water tankers. Building caretakers were able to supplement this data since they manage water deliveries from these sources.

Interviewees were recruited with a convenience sampling process. This was based on interviewees' ease of accessibility, willingness to participate, and geographic location in the two communities (Etikan, 2016). Random sampling was not possible at the time given the political instability during the data collection period which included protest and riots that led to the resignation of the Prime Minister (BBC, 2019). The sampling process started with one main contact in each community. At the end of each interview, the interviewees would share the contact information of their friends in the same community, including their neighbors. The researcher would then contact by phone the new list of names to take appointments. The process was repeated until a sample size of around 50 was reached in each community (52 in Aicha Bakkar and 53 in Verdun). The sample size was based on sample sizes used in similar studies within the field of water insecurity and informal water systems (ref: Rosenberg et al., 2007; Jepson & Vandewalle, 2016; Walter et al., 2017), and meets the minimum standards for valid statistical analysis given political and financial constraints (Walter et al., 2017).

Data Analysis

The analysis was based on two main components: estimating household income (from occupation, age, and level of education of interviewees), and identifying the total cost of water supplied by water source. Once income levels and costs were estimated, it was possible to compute affordability ratios.

Choosing Income over Expenditure

The government's statistical agency (CAS, 2012) provides aggregated data on household expenditure (income and water costs), but the data has substantial limitations. Reported incomes are not representative of all Lebanese income groups. The statistical agency's monthly income categories range from $400[2] (the minimum wage) to $1,600. These numbers are too low. The numbers are lower than the average income of the lower income community (Aicha Bakkar). Moreover, they are not aligned with other references that show monthly average gross salaries ranging from $2,600 to $3,100 (Salary Explorer, 2020; Average Salary Survey, 2020). When it comes to water costs, the statistical agency uses only subscription fees of the formal piped system. However, real household water expenditure includes purchasing alternative informal sources (such as for water tankers, wells, and bottles) that the statistical agency does not show. These limitations pushed us to an income approach, as it was easier to estimate household income and water costs separately by collecting this data through the study's survey as explained below.

Income

To compensate for the absence of census data on income, income levels were derived from survey questions on occupation, age, and level of education of interviewees. Estimation of incomes was based on two main databases. The first was from a private research center, InfoPro Research (InfoPro Research & Lebanon Opportunities, 2016) which gathers data of income per occupation of 11 sectors (Advertising,

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[2] All costs in this study are in $US.

Banking, Construction, FMCG, Hotel, Insurance, IT, Manufacturing, Restaurant, Retail, and Travel & Tourism Sector) and years of experience. The other source was based on an online platform *Average Salary Survey* (Average Salary Survey, 2020) that shows lump sum Lebanese salaries by career and field. Both sources complement each other: the first has a more refined division of income, for each sector, as it shows the different salaries of multiple positions per years of experience. For example, the banking sector is divided into 13 positions and 9 categories of years of experience. However, it does not cover a wide range of sectors. The second reference covers more sectors without detailing income levels. The survey answers provided the occupation and age of each interviewee, which was used as a reference for their years of experience. It was thus possible to group occupations into 22 categories and estimate their corresponding incomes.

Costs and Volumes

The cost for each water source was estimated from survey results on the timing, amount of water delivery, and the cost per source. Cost data were normalized across all interviewee responses to reflect cost per person per day or cost per household per year.

Scale, temporality, and seasonality

Scale, temporal, and seasonal variations were accounted for when analyzing the timing of delivery per source. Different sources are needed at different times by different households, as reflected in the variable water purchasing patterns presented by the interviewees. In terms of scale (**Figure 3**), the formal piped supply, tankers, and wells are usually delivered to buildings, whereas bottles are delivered to households. As for timing, piped water supplies usually are delivered every 48 hours (for a continuous period of around 3 hours in summer and 7 hours in winter), bottled water is delivered daily or weekly, tankers tend to deliver water every two weeks or monthly, and wells have no identified pattern delivery timing.

Demands and supplies also change seasonally. For example, during the winter, people tend to consume less water, especially for non-drinking needs, and the piped water is delivered with a higher pressure, which decreases demand for supplementary water from tankers and wells. Since data on seasonal and flow rate variations does not exist, the survey included a question on peoples' perception of summer and winter seasons by asking interviewees about the months of greatest water shortage. The total average of summer months was used when calculating total volume used for the entire sample population.

Formal piped water service

Cost: Based on the official subscription fees, Lebanese households pay a flat rate of $200 per year for one cubic meter (m^3) per day for piped water supplies.

Volume: Since piped infrastructure supply is not metered, estimated final delivered volumes were based on initial average supply values from the water establishment, adjusted with leakage percentages and estimations on summer reduced supply (because of higher intermittence and lower flow).

1. Initial average supply by the water establishment= 180 Liters/Person/Day (MoEW, 2010; Jaafar et al., 2020).
2. Infrastructure supply losses amounts to 45% due to leakages (Shaban 2020; Bulos and Yam, 2021).
3. Summer months = 4 months, winter months = 8 months (Based on interview answers, 50% of sample population experience lower flows from August until November. So, we considered summer to be four months, and winter to be eight months).
4. Supply in summer months drops by 40% (based on interview answers and water establishment engineer, El Asmar, personal communication, July 7, 2021).

The final delivered volumes are based on adjusted summer and winter supplies calculated first separately and then summed based on their weighted averages detailed below:

- Adjusted delivered supply = 3,427 (liters/person/month). Based on the official supply rate of 180 liters/person/day, adjusted by 0.55 (45% of losses from leakage), and by weighted months' reduced supply values.
- Weighted months' reduced supply values = 10.4 = winter months + weighted summer months:
    - Winter months = 8
    - Weighted summer months = 4 x 0.6[1] = 2.4 ([1]based on 40% of reduced summer supply).

Bottles

Cost and Volume: Survey answers showed the number, volume, and cost of bottled water purchased per household per week. Unit conversion calculations (from household per week to person per day) provide total cost and volumes of bottles per person per day.

Tanker

Cost and Volume: Survey answers showed the number, volume, and cost of water tanker deliveries purchased per household (or building) per week. It was possible to compute the total cost and volumes of water delivered by tankers by converting the units from household (or building) per week to person per day.

Wells

Volume: The volume delivered from the wells was based on the flow rates of pumps installed for buildings. The average flow rate is around 18 liters per minute. It was computed by averaging all flow rates of households based on the formula: $Q = p\ (6116\ 10^{3}\ \mu)\ /h\ d$, where:

- p = power (kW), 0.7457 kW. The typical household pump sizes are around 1HP, based on the water establishment (El Asmar, personal communication, February 14, 2020)
- μ = pump efficiency (0.70)
- h = differential head, depth of the wells (m). Depth intake is usually less than the depth of the well. However, since depth intake was not available, it was assumed that the pumps are located at the ground level and that residents were pumping water from the bottom of the pumps which was considered as the pumping height. The interviewees provided the depth of the well, however for the missing depths an average of 70 meters was taken into account, which is based to the average of the wells depth from the interview answers.
- d = density (1000kg/m^3).

Cost: The cost of wells includes costs of drilling, pumping, and treatment (through reverse osmosis units). The drilling cost was based on the Lebanese market of drilling ($100 per meter of depth) and the assumption that wells have a lifetime of 25 years. We converted total drilling cost into daily cost per person. The well pumping costs were calculated by multiplying the pumping costs with pumping operation hours. The pumping costs were based on the formula: $C = Q \rho g h c / (3.6 \times 10^6 \mu p \mu m)$ (detailed below) and the survey answers indicated the pumping operation hours.

- Q = volume flow (m^3/hours) = 1.284 m3/hours
- ρ = density (1000kg/m^3).
- g = acceleration of gravity (9.81 m/s2).
- h = differential head, depth of the wells (m). Same as above, pumping height was based on the well depth since depth intake data was not available.
- c = cost in kW per minute ($/kW). It was based on the Lebanese cost of kW of 0.0958 $/kW/minute.

Reverse osmosis (RO) unit costs were estimated by summing initial investment costs, monthly maintenance costs, and pumping costs. The survey answers provided information on initial investment costs and monthly maintenance costs per building. For the investment cost, we assumed that RO units have a lifetime of 15 years. We then converted this value into daily cost per person. For maintenance costs we converted the reported values, per building per year, to person per day. We relied on pumping information from the wells to estimate the total pumped volume and cost. The survey data provided information on the operation hours of RO units. Combining this information with the flow rate from well pumps resulted in estimated cost per liter ($/L).

The survey asked about monthly energy costs, but the given answers were unreliable and insufficient and were omitted from the final analysis. Moreover, the data was omitted for 3 interviewees as their survey answers indicated that they had an RO system, but it was not in use.

Internal pumping costs

Cost: As mentioned earlier, households try to maximize their on-site storage capacity with underground and roof reservoirs to capture all water available from the formal piped supply. This translates into additional internal building pumping from the underground reservoirs to the roof-level reservoirs. The additional internal pumping costs were calculated using the same formula as for the well, and we multiplied the values with the total hours of operation of the internal pumps. Similar to the well data, the pump size was also assumed to be equal to 1HP. The differential head was taken as the buildings' heights. Most pumps operate automatically when the lower reservoir reaches a set water level. Therefore, interviewees did not know how long the pumps operate. We therefore assumed the pumps operate automatically once the household receives municipal water. The interview answers showed the total hours of formal supply. This information was used as the operation hours of internal building pumps.

Results

The results start by showing water affordability thresholds for both communities. Affordability ratios are based on total water sources costs compared to each community's median income. Since water costs depend on supplied volumes, we start with results on volumes and then show the cost implications of the multiple water sources. We end with the communities' median incomes.

Water (un)affordability

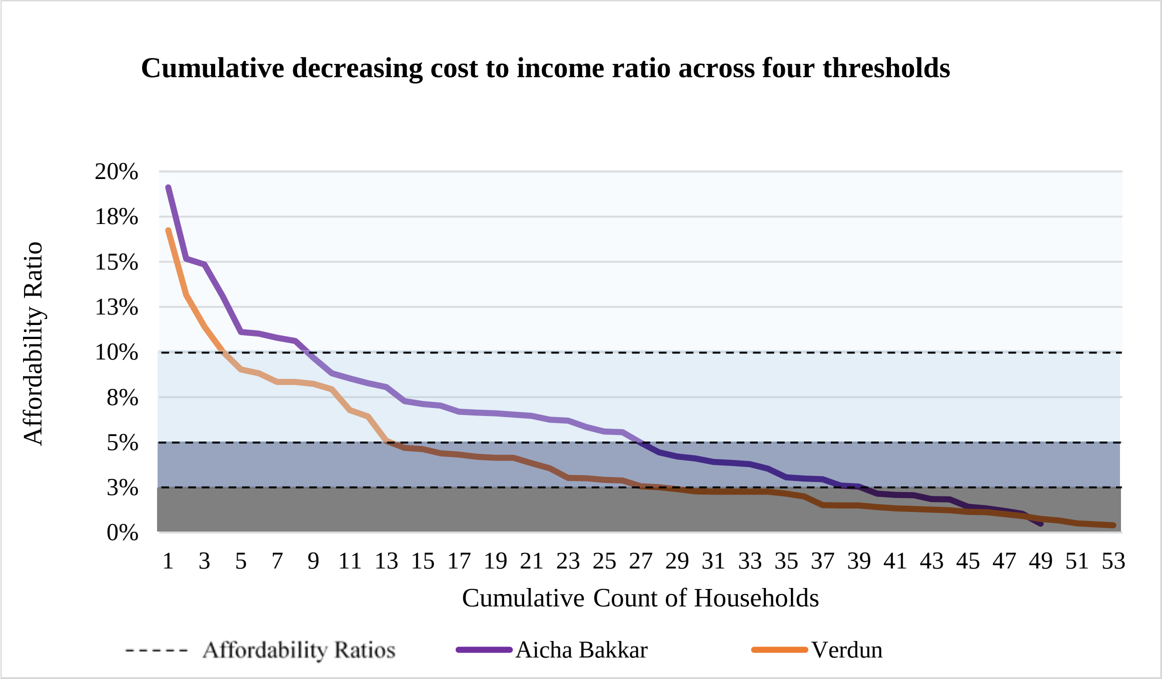
To assess water affordability, water sources costs were compared to median income in three ways. 1) We analyze overall affordability ratio for the entire population by comparing total water costs to median income of the total sample population; 2) we analyze each community's affordability ratios by comparing average water costs with average median income per community; 3) finally we analyze per household affordability ratios by comparing water costs and median income for each household.

Overall affordability ratio for the entire population is 6%, in terms of total average water cost divided by median income. Most affordability thresholds from the literature (from **Table 8** and **Table 9**) range from 3% to 5%, so water is rather unaffordable for the entire sample population.

The average cost to median income ratios for each community show Aicha Bakkar at around 10% and Verdun at around 4%. So even though Aicha Bakkar households pay less overall for water ($1,727 versus $2,514, see **Figure 7**), their (un)affordability ratios are 2.2 times less than for Verdun. This is because the median income in Verdun is much less than for Aicha Bakkar.

Figure 4 shows a more detailed analysis with a per household income-to-cost ratio distribution, by taking the cumulative percentage of each households, ranked in decreasing order (Martins et al., 2019). The graph shows that, on the far left of the graph, there is a high percentage of Aicha Bakkar households with higher income-to-cost ratio than Verdun households. Water is generally less affordable for lower income households, as elaborated further in **Table 11**. Nevertheless, on the far right, a small percentage of households in Aicha Bakkar have a lower percentage of water costs than Verdun households. This can be linked to lower income households trying to reduce their water costs, thus, end up with low affordability ratios. This indicates that water is, sometimes, more affordable but not adequate in supply for lower income communities.

Figure 4 – Cumulative decreasing distribution affordability ratios across four affordability levels.



Based on threshold ranges from the literature, we developed four brackets based on whether households pay less than 3%, between 3% and 5%, between 5% and 10%, and more than 10%, as indicated in **Table 11**. In Aicha Bakkar, 45% of the households allocate less than 5% of their income for water and 18% of households pay less than 3% of their income for water. However, most of this population (around 55%) pays above 5% of their income for water, and 18% of households have highly unaffordable water, paying more than 10% of their income for water. In Verdun, most of residents generally access affordable water services, given their higher income. 72% of households are allocating less than 5% of their income for water and 45% of households pay less than 3% of their income for water. Meanwhile, 8% of this population is still paying more than 10% of their income to water.

Table 11 – Percentage of households within each (un)affordability bracket threshold.

Affordability Threshold: **Income-to-cost ratios**	**Aicha Bakkar** **Percentage of households**	**Verdun** **Percentage of households**
Water is Highly Unaffordable **Above 10%**	18%	8%
Water is Unaffordable **Between 10% and 5%**	37%	21%
Water is Moderately Affordable **Between 5% and 3%**	27%	26%
Water is Affordable **Less than 3%**	18%	45%

The three affordability methods presented above (overall sample population, per community, and per household ratios) show that generally water is rather unaffordable in Beirut. Overall sample population affordability ratio of 6% is higher than most other ratios found in the literature (refer to **Table 8** and **Table 9)**. Moreover, when comparing average income per community, we see stark disparities. Even though, lower income community of Aicha Bakkar has lower total water costs, the community accesses less affordable water paying 2.2 times more, relative to income, to secure water. The per household analysis highlights the scale of disparities further; more than half of these residents (55% of households), spend more than 5% of their income on water.

Sensitivity in Affordability Analysis

In terms of uncertainty in the relative unaffordability presented above, both extremes (**Table 11** very high unaffordability above 10% and affordability lower than 3%) are susceptible to errors in income estimation. Some households are likely to have additional income or wealth that this study does not capture, which would lower the high unaffordability ratios. This means, that if we consider all income or wealth venues of residents, we might find that water is more affordable than what is presented in this study.

Moreover, to analyze these results further, we develop a sensitivity analysis. Based on databases on Lebanese incomes (Salary Explorer, 2020; Average Salary Survey, 2020), we see that lowest incomes estimates can be 4 times less than our results (taking into consideration that lowest income in Lebanon can be equal to $355 compared to our results of $1,453), whereas highest income estimates can be 2.5 times higher than our results (highest incomes can reach around $11,600 compared to our results of $4,775) (this is further developed in the last section of the results). If we take these extremities incomes (lowest and highest values), we realize that affordability disparities are worryingly higher.

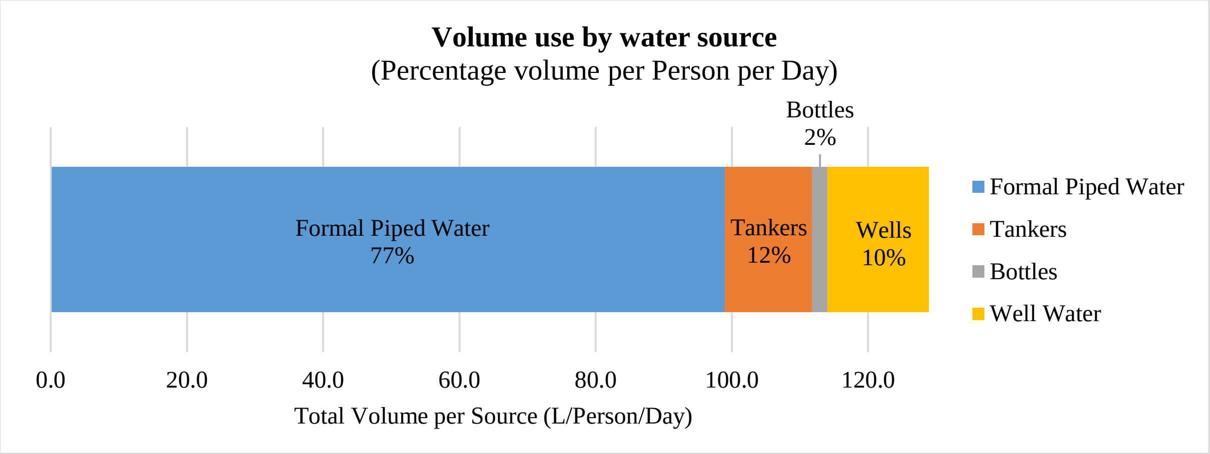
The cost to median income ratios for lowest incomes increases up to 40% (compared to our results of 10%). Our per household analysis (**Figure 4**), indicates that no lower income household is paying more than 19% their income to water. Hence, 40% is an extreme unaffordability ratio, taking the example of a person earning less than the minimum wage.

The cost to median income ratios decreases for highest income to 1.7% (compared our results of 4%). However, our per household cumulative analysis (**Table 11**) shows that 45% of higher income communities have an affordability ratio less than 3%, hence we could conclude that a big parentage of higher income communities do have lower affordability ratios, and that some might be very close to 1.7%.

Volume use by source and their seasonal variation

As indicated in **Figure 5,** of the total water volume supplied per day, roughly 77% comes from the formal piped system, followed by tankers (12%), wells (10%) and lastly bottled water (2%). The volumes supplied by the wells, tankers and bottles are based on the survey answers, and the formal piped volume is estimated (based on official supply values, intermittence estimates and leakages percentages) as we don't have exact volume supplied to the communities.

Figure 5 – Volume by water source (L/Person/Day).



The official supply estimate by the Ministry of Energy and Water is an average of 180 liters/person/day (MoEW, 2010; Jaafar et al., 2020). We adjust this value for roughly 45% losses to pipe network leaks, so average delivered piped supply is around 99 liters/person/day (**Table 12)**. Moreover, based on this value, we estimate seasonal variations accounting for decreased summer supply and weighted average of summer/winter months. Supply from the formal piped water decreases in summer by 40% (from 114 liters/person/day to 69 liters/person/day). This is mainly from reduced summer supply due to increase intermittence and reduced flow rate reported by interview answers and water establishment engineers (El Asmar, personal communication, July 7, 2021). Usually people increase water use in summer by 10% (Wada, 2001). To compensate for the reduced supply and increase consumption, our results show people increase their informal water sources use. **Table 12** shows that tanker water demand increases in summer almost 20 times, and well water demand increases almost 6 times. Drinking water doesn't change, people drink year-round about 2 liters/day. These added sources result with a total 10% increase of total supply between summer and winter with 143 liters/person/day compared to 129 liters/person/day respectively.

Table 12 – Average of supply volumes (Liter/Person/Day).

	Average volume per Person per Day (independent of season)	**Winter volume per Person per Day**	**Summer volume per Person per Day**
Formal Piped Water	99	114	69
Bottles	2	2	2
Tankers	13	2	48

Well Water	15	11	24
Total	**129**	129	143

Volume comparison between communities

Table 13 shows overall water use volumes by source for Aicha Bakkar (low -income) and Verdun (high-income). These adjacent communities share a similar water intermittence schedule from the piped infrastructure. So both communities have similar piped water volumes of roughly 99 liters/person/day. The main differences are that Aicha Bakkar has a higher supply of water from tankers, whereas Verdun, has a higher supply from wells. This is related to the cost per source, discussed further below. Moreover, 10% of Aicha Bakkar households reported being very careful in how they consume water, which also might reduce overall volumes.

Table 13 – Water supply differences by source for Aicha Bakkar and Verdun communities (Liter/Person/Day).

	Aicha Bakkar L/person/Day	**Verdun L/person/Day**
Formal Piped Water	99	99
Bottles	2	2
Tankers	19	7
Wells	8	21
Total Volume	128	130

Cost comparison per source between communities

As indicated in **Figure 6** and **Table 14,** the informal sources have the greatest cost, but much smaller contributions to delivered water volume. Bottled water has the largest share of total costs because it is by far the most expensive water source per liter at $0.52/liter. **Figure 6** considers the total cost per source, including the delivered volume, whereas **Table 14** shows the cost per liter regardless of delivered volume.

Figure 6 –Household water costs by source, including delivered volume ($/Person/ Day).

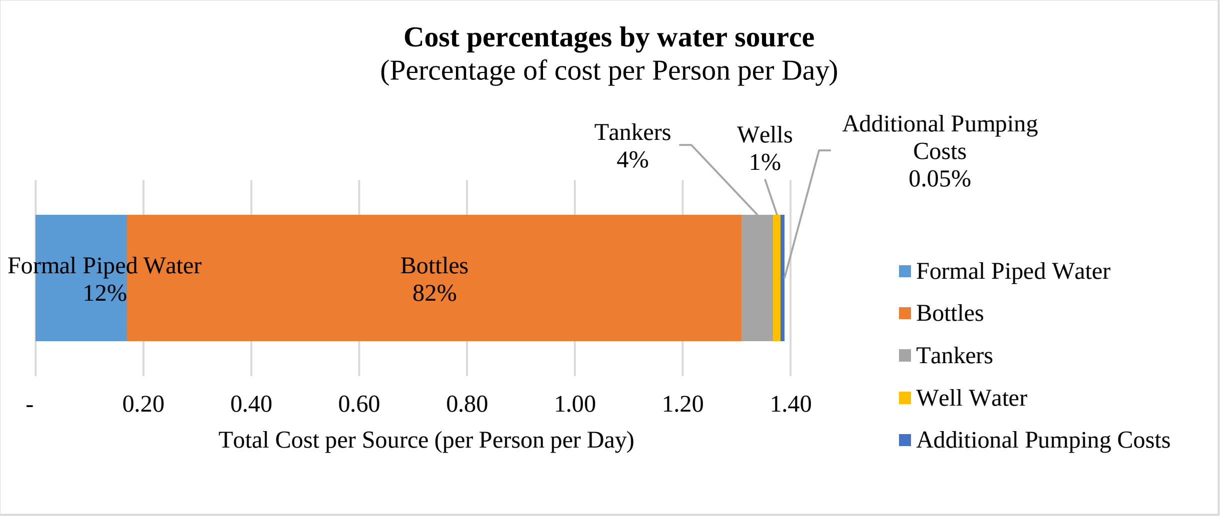


Table 14 - Cost breakdown per source of 1 liter of water ($/Liter).

	Unit Cost ($/L)
Formal Piped Water	0.0017
Bottles	0.5238
Tankers	0.0045
Well Water	0.0010

Disparities between income communities

Table 15 highlights total costs per person per year (accounting for the volume consumed per source) and cost per liter for different sources for both communities. When comparing these communities, the differences of yearly cost per source are mainly from the sources' cost per liter and supplied volume as detailed below.

Both communities' water cost is mostly for bottled water, the most expensive source per liter, and the smallest source by water volume. People rely mostly on bottled water for drinking (and sometimes for cooking), because distrust in the quality of other delivered water (Haddad, 2002; Zawahri et al., 2011). However, total per capita cost difference between the two communities is around $188, a 46% of difference ($412 for lower income Aicha Bakkar and $600 for higher income Verdun). The cost per liter of bottled water for Verdun is around 0.6$/liter and around 0.4$/liter for Aicha Bakkar. Even though both communities have an average household size of about 4 people, Aicha Bakkar residents buy around 10 bottles of water on average during a summer week, whereas Verdun residents buy up to 4 times this quantity, up to 41 bottles per summer week. These differences are elaborated in the discussion section. The second most expensive supplied source is the formal piped-water taking up to $53 of each person's yearly water cost in Aicha Bakkar and $71 in Verdun. Even though the cost per liter for both communities is the lowest with 0.0015$/liter and 0.0020$/liter respectively, the formal piped water system still supplies by far the largest volume, which explain the high total yearly cost.

Residents of Aicha Bakkar spend 8% of their income on tankers, while the wealthier households in Verdun spend only 2%. This might also be related to costs per liter where Aicha Bakkar residents pay around 0.0048$/liter versus Verdun residents pay around 0.0036$/liter. The difference in cost of tankers are mainly related to economies of scales, as Verdun residents can afford larger tankers with lower unit costs. This is further elaborated in the discussion section.

For wells, Verdun residents spend around 1% of total water supply cost. Differences in well costs could be linked to the higher income households in Verdun having more wells. The total number of wells used in Verdun (24) is 50% more than Aicha Bakkar (17). Moreover, in Verdun, 17% of buildings rely on reverse osmosis to treat well water, and no evidence was found of RO units for Aicha Bakkar's wells. Additional internal pumping cost differences are due to building height differences. Aicha Bakkar tends to have shorter buildings with an average height of 27 meters whereas buildings in Verdun have an average height of 38 meters.

Table 15 – Differences of supply costs per sources for both communities.

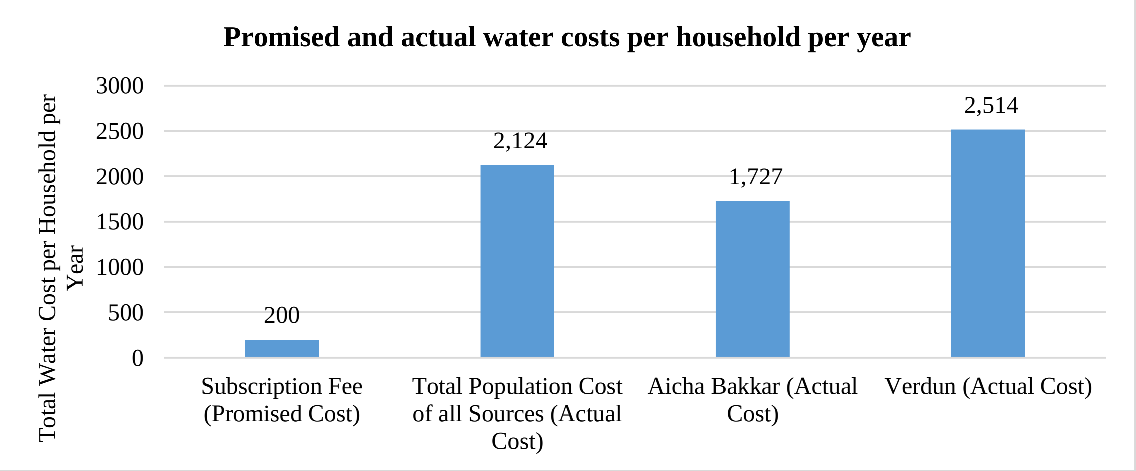
	Aicha Bakkar			**Verdun**		
	Total cost of per Person (taking into account yearly supply) $/Person/Year	% of cost per source	Cost per Liter $/liter	Total cost of per Person (taking into account yearly supply) $/Person/Year	% of cost per source	Cost per Liter $/liter
Formal Piped Water	53	13%	0.0015	71	12%	0.0020

Bottles	324	79%	0.4352	507	84%	0.6004
Tankers	33	8%	0.0048	9	2%	0.0036
Well Water	1	0.2%	0.0002	10	2%	0.0047
Additional Pumping Costs	2	0.4%	0.0000	3	1%	0.0000
Total	412			600		

Promised and actual costs

Added costs from informal sources increase the cost communities actually pay for water. The subscription fee for households is around $200 per year for a “promised” volume of a 1m^3 per day, that is not reliably delivered. In reality, households (for the total sample population of both Aicha Bakkar and Verdun communities) pay an average of $2,124 per year, around 10 times more than the subscription fee (**Figure 7**). As a total cost, households in Verdun pay an average of $2,514/year/household, or 50% more than households in Aicha Bakkar ($1,727/year/household). As discussed and based on **Table 15**, the additional costs result mostly from increased cost of bottled water and local well supplies (including extra pumping and treatment costs). In addition, there are capital and maintenance costs of underground and roof reservoirs, which this study does not include.

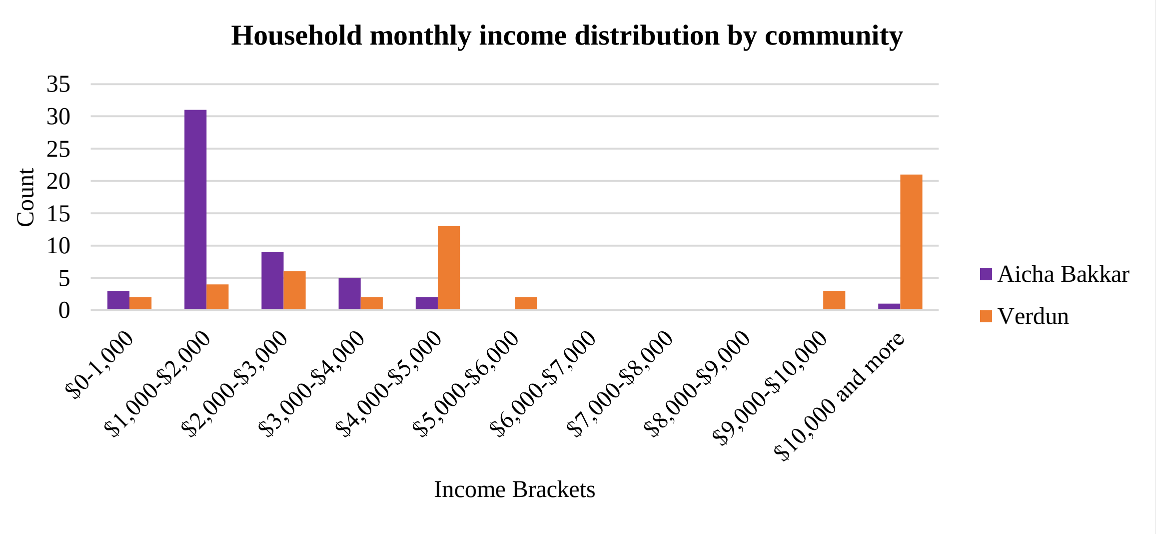
Figure 7 – Formal piped system and actual water costs for total sample population and individual communities ($/Household/Year).



Income distribution of both communities

Average income level for the entire sample population is around $2,792. Sixty percent of Aicha Bakkar's salary is $1,000-$2,000/month, and 64% of Verdun's salary is at or above $4,000-$5,000/month (**Figure 8**). Median monthly income for households in Aicha Bakkar, is around $1,400 and around $4,700 for households in Verdun. The average income levels obtained in our study are similar to overall Lebanese household income levels that show that monthly average income per person is around $2,600 and $3,100 (Salary Explorer, 2020; Average Salary Survey, 2020). However, some differences are highlighted when looking at highest and lowest values. Based on Lebanese incomes databases, lowest income values can reach $355/month (Salary Explorer, 2020; Average Salary Survey, 2020), which is 4 times lower than our average. However, it is important to note, that this is lower than the Lebanese minimum wage of around $450/month (MFE, 2021). Highest income values can reach up to $11,600/month (Salary Explorer, 2020; Average Salary Survey, 2020), which is around 2.5 times higher than our average. Income differences of lowest and highest values show that Aicha Bakkar is a lower income community, but does not fall into extreme poverty, and that Verdun is a higher income community, but does not fall into extreme affluent levels. These differences are reflected in the affordability ratios presented early in the results section.

Figure 8 – Household monthly income distribution by community.



Discussion

In areas where formal piped water supplies are insufficient in quantity, quality, or reliability, informal water sources are used to supply remaining daily water demands of different income groups. The study shows that most water costs are for informal sources, with bottles being the most expensive source, and water affordability impacts differ for different income communities. To identify water affordability disparities, this study develops a framework that accounts for the cost of multiple formal (piped infrastructure) and informal water sources of high and low- income communities.

Compared with other studies, water for the entire sample population is fairly unaffordable with some households in both communities paying more than 10% of their income to water. This is far more common in Aicha Bakkar, and the analysis highlight affordability disparities between these communities. Even though the lower income community (Aicha Bakkar) has lower total water costs, the community accesses less affordable water paying 2.2 times, relative to income, for water. Per household analysis highlights these disparities further and shows that more than half of these residents (55% of households), spend more than 5% of their income on water. Moreover, this analysis shows that for the lowest Lebanese income values, some households might pay 40% of their income to water. The greater purchasing capacity of higher income households makes them more autonomous for current and future water security. A major difference was the number of purchased bottles between both communities. Verdun residents buys up to 4 times more bottles than Aicha Bakkar residents. These large differences are mainly related to disparities in accessing water bottles. Verdun residents can afford more expensive brands. Moreover, they buy more bottled water for drinking and cooking. Whereas Aicha Bakkar residents tend to buy cheaper brands and generally boil tap water for cooking (increasing their energy costs).

Cost and volume differences between higher and lower income communities are not only related to the purchasing power of Verdun residents, but can also be explained by factors related to urban structure and economies of scale. For example, Aicha Bakkar has smaller streets, so only smaller tankers, which are more expensive to operate per unit delivered, can enter the area. Moreover, Verdun residents have larger storage capacities related to their larger building footprint. Even though we did not measure the storage capacity per community, we can assume that, since the reservoirs are usually stored under and above the buildings, the storage capacity is proportional to the building's footprint. Thus Verdun residents have the capacity to refill and store more water at each cycle, by purchasing larger tankers (that are cheaper per unit delivered), and fill more water from the piped infrastructure (the cheapest source).

The study considers some coping behavior related to seasonal choice of sources and change in consumption patterns. For example, the study calculates added coping costs related to increased pumping, treatment for water within individual buildings. For both communities, cost differences between summer and winter can be explained by costs per source, where people increase use of cheaper sources, which in this case are tanker trucks. Also, for lower income communities, the study reported households changing consumption patterns by being very careful when they use water as they cannot afford the added costs of informal sources. They schedule highly intensive water activities (i.e., washing clothes) when the municipal water is supplied (since it is the cheapest source). Changing behavior to adapt to a certain supply schedule or worrying about having enough water for household activities are important psychological dimensions of water insecurity (Young et al., 2019). For the higher income communities, coping costs are linked to accessing improved technologies, such as treating water through expensive treatment by reverse osmosis, accessing more expensive drinking water bottles (MoPH, 2020), and also related to increased pumping costs for taller buildings. Thus higher income households become less impacted by overall municipal water shortages, as they can buy and pump larger water volumes and still have access to good water quality.

Recommendations: How to Address Informality

A major problem driving water access and affordability disparities is that the formal water subscription fees are a small share of total water cost. The very low cost of formal service affects overall revenue and budget of the water utility which limits its capacity to upgrade and maintain the water infrastructure. The piped infrastructure currently has up 45% of losses in its distribution systems (Shaban 2020; Bulos and Yam, 2021). This creates a vicious cycle where the piped water system's reduced fees and budget result in high supply intermittence, pushing household to rely more on alternative informal water sources. This leads to affordability disparities between low and income neighborhoods. Using informal sources becomes a necessity rather than a choice.

This opens the discussion on how the role of informality in producing these disparities. Informality, initially had a negative connotation in the literature, referring to activities of the urban poor (Hart, 1973; Moser, 1978; AlSayyad, 2004). However, scholars have more recently recognized that informal activities can often better adapt and are sometimes more suitable than formal piped infrastructure (Revell, 2010; Ranganathan, 2014), especially in terms of quantity and quality. Our case study shows that in terms of quantities, informal sources deliver up to 23% of total volume, and for better water quality, households rely on bottled water. However, we need to be critical when associating resilience (Revell, 2010) with informality. Even though, generally, informal sources help people overcome their daily water shortages, by accessing improved quantities and qualities of water, this is not homogenous across different communities of different socio-economic levels and results in water disparities and higher costs overall.

Our case study shows that formal and informal systems work in tandem (Peloso and Morinville, 2014; Ahlers et al., 2014). While informal sources provided the needed volumes, formal piped infrastructure provides an affordable service. So we can think of hybrid strategies to upgrade water quantity, quality and cost.

A first strategy should target upgrading the piped infrastructure to reduce losses. This strategy is currently being developed by the Lebanese water utility as an indirect method to eliminate informal tankers

(Hoayek, personal communication, September 8, 2019). By reducing water losses, the water utility hopes to supply more water to households and decrease demand on tankers. Another strategy being implemented by the water utility is installation household water meters (EBML, 2021; Hoayek, personal communication, September 8, 2019), which will help monitor losses and reduce leakage.

To upgrade the piped infrastructure, the water utility could try to increase its budget by increasing service rates. People are clearly paying added costs for other sources, so they might be willing to pay more for piped service. To estimate increased service rates the water establishment can calculate whether the added costs that people are already paying would be sufficient to upgrade the infrastructure. However, this might be challenging politically. Public institutions are poorly managed (El Fadel et al, 2003; Alameddine et al 2018) and peoples' lack of trust in public institutions might result with unwillingness to pay more, knowing that they might never receive the promised volumes. One way to move forward is to start with a pilot project, where the water institutions could gain public trust by proving that it is capable of delivering a safe and reliable water quantity and quality.

Other strategies could be to improve quality and cost. Bottles are currently the most expensive source. We recognize the dangers of commodifying water (Bond, 2004). However, in areas where people do not trust the quality of tap water (Haddad, 2002; Zawahri et al., 2011), bottles are a necessity (Walter et al 2017). Financial strategies and subsidies could reduce the price of bottled water, making them more affordable for both high and low income communities. Other public health strategies should be developed to control the distribution of unregistered bottles of dubious quality. For example, from our survey, out of the 26 drinking bottle brands mentioned by households, only 8 (31%) were registered by the Ministry (MoPH, 2020). Another strategy could focus on monitoring the quality and cost of informal water tankers (Constantine et al 2017). Some scholars have suggested formalizing informal tankers (Ahlers et al., 2013), through management frameworks that target water tanker quality standards and tariffs (Constantine et al 2017). However, this might result in a monopoly by larger water tanker companies that already control the market, as they might be the only ones able to engage and negotiate with public institutions. Also they might be the only ones able to afford formalization's added costs from registration fees, licenses and taxes more than smaller companies (Ahlers et al., 2013).

Limitations

The study's main challenge was the absence of accurate census data on household expenditures and income. Available governmental data on household expenditure is not representative for all Lebanese income groups.

The study follows an income-based approach to estimate water affordability, however household income data are not particularly reliable. Income values were estimated based on proxy data obtained from survey answers on age, occupation, and education level, coupled with salary data from different non-governmental databases. Moreover, the survey relied on one income source per household. However, households might have multiple income sources (formal or informal revenues) not identified in this study (Mack & Wrase 2017; Martins et al., 2019). Computed income might be less than actual income. Hence, considering actual income levels might lower the high unaffordability ratios that were presented in this study.

The study used gross income to calculate affordability levels. However, gross income might overestimate household's financial capacity to pay for water, as not all income is available to pay for water (Goddard, 2019, p. 19). Households that are paying high rates, will be further disadvantaged economically as they cannot afford other goods and services such as housing, food, health care, and home energy. Recent affordability matrices offer more holistic perspectives by accounting for these factors. They used disposable income, acknowledging that households need to pay for other services (Davis & Teodoro 2014; Teodoro, 2018). In areas where census data are unavailable, as is the case for Beirut, it is challenging to estimate disposable income. Further studies on affordability of the Lebanese water system could try to consider essential cost of living variables to show a more realistic overall household water and living affordability levels.

The study does not account for consumption patterns, apart from 10% of lower income households mentioning that they change their consumption habits by following the formal piped supply's intermittence schedule. Future studies could look into basic water needs and uses which could help identify whether households are receiving enough water. This can highlight if consumption is too high indicating consumption for luxury water or too low because people are not accessing sufficient water for their basic needs (Komarulzaman, 2017, p.13; Teodoro, 2018; Vanhille et al., 2018).

Conclusions

This study compared income-based water affordability ratios for two communities of different income levels, in Beirut, Lebanon. In both communities, informal water sources are around 88% of total water cost, but provide only 23% of average water volume. Water affordability is an issue for both communities, as they both pay around 10 times more for total water services compared to the cost of water from formal piped water system. This study highlights further water disparities. The lower income community of Aicha Bakkar has lower total water costs, the community accesses less affordable water paying 2.2 times more for water, relative to income. The per household analysis highlights the scale of disparities further and shows that more than half of these residents (55% of households), spend more than 5% of their income on water. Higher income communities have a higher purchasing capacity: they can afford more expensive water brands, especially for water bottles; and they can afford reverse osmosis units, hence are less impacted by well water quality issues. Also they have the capacity to refill and store more water because of larger storage capacities that are linked to larger building. This results in them being less impacts by overall water insecurity issues related to qualities and quantities.

Our analysis shows that affordability disparities can be far worst, if highest and lowest Lebanese income values are taken into consideration. Household that earn less than the minimum wage might be paying around 40% of their income to water.
The study also analyzed coping behavior and costs Lower income communities change consumption pattern to use intensive water activities when municipal water is supplied; and coping costs, from treatment technologies and increased water pumping, are higher for higher income communities because they are able to install domestic reverse osmosis units.

Solving issues of equity and affordability, of multiple water sources, is complex. This study shows that formal and informal systems are entangled, and water affordability issues are embedded in other aspects of water quantity and quality, and urban and community structure. Hence we propose strategies to improve quantity, quality and cost of multiple water sources. However, in countries, such as Lebanon, that already suffer from poor management from public institutions (El Fadel et al, 2003; Alameddine et al 2018), it becomes challenging to improve the overall system. It is even more difficult to apply them, in a transparent and efficient way, and impose change on end-users that have an inherent lack of trust in public institutions.

References

Ahlers, R., Perez Güida, V., Rusca, M., & Schwartz, K. (2013). Unleashing entrepreneurs or controlling unruly providers? The formalisation of small-scale water providers in Greater Maputo, Mozambique. *The Journal of Development Studies*, *49*(4), 470-482.

Ahlers, R., Cleaver, F., Rusca, M., & Schwartz, K. (2014). Informal space in the urban waterscape: Disaggregation and co-production of water services. *Water Alternatives*, *7*(1), 1-14.

AlSayyad, N. (2004). Urban informality as a "new" way of life. *Urban Informality: Transnational Perspectives from the Middle East, Latin America, and South Asia*, 7-30.

Alameddine, I., Tarhini, R., & El-Fadel, M. (2018). Household economic burden from seawater intrusion in coastal urban areas. *Water International*, *43*(2), 217–236.

Amit, R. K., & Sasidharan, S. (2019). Measuring affordability of access to clean water: A coping cost approach. *Resources, Conservation and Recycling*, *141*, 410–417.

Average Salary Survey. (February, 2020). *Lebanon Salary*. https://www.averagesalarysurvey.com/lebanon

British Broadcasting Corporation (BBC) (October, 2019). Lebanon crisis: PM Hariri offers resignation amid protests. *British Broadcasting Corporation*. Retrieved from: https://www.bbc.com/news/world-middle-east-50225100.

Banerjee, S. G., & Morella, E. (2011). *Africa's Water and Sanitation Infrastructure: Access, Affordability, and Alternatives*. The World Bank.

Baquero, O. F., Gallego-Ayala, J., Giné-Garriga, R., de Palencia, A. J.-Fernández., & Pérez-Foguet, A. (2017). The Influence of the Human Rights to Water and Sanitation Normative Content in Measuring the Level of Service. *Social Indicators Research*, *133*(2), 763–786.

Bond, P. (2004). Water commodification and decommodification narratives: pricing and policy debates from Johannesburg to Kyoto to Cancun and back. *Capitalism Nature Socialism*, *15*(1), 7-25.

Bulos, N & Yam, M. (2021, April 2). Climate change and corruption endanger an ancient valley in Lebanon. *LA Times*. https://www.latimes.com/world-nation/story/2021-02-21/bisri-valley-water

Council of Ministers Central Administration of Statistics (CAS) (2012). *Household Expenditure*. http://www.cas.gov.lb/index.php/demographic-and-social-en/householdexpenditure-en

Christian-Smith, J., Balazs, C., Heberger, M., & Longley, K. (2013). Assessing water affordability. *A pilot study in two regions of California, Pacific Institute.*

Clasen, T., McLaughlin, C., Nayaar, N., Boisson, S., Gupta, R., Desai, D., & Shah, N. (2008). Microbiological effectiveness and cost of disinfecting water by boiling in semi-urban India. *The American journal of tropical medicine and hygiene*, 79(3), 407-413.

Constantine, K., Massoud, M., Alameddine, I., & El-Fadel, M. (2017). The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of Environmental Management*, *188*, 85-94.

Davis, J.P. & Teodoro, M.P. (2014). Financial Capability and Affordability. In *Water and Wastewater Finance and Pricing*, 4th ed (Raftelis, G. A. editor). New York: Taylor & Francis.

Eaux de Beyrouth et du Mont-Liban (EBML) (2021, March 01). Latest Projects. Retrieved from https://ebml.gov.lb/projects.php?lang=en

El-Fadel, M., Maroun, R., Semerjian, L., & Harajli, H. (2003). A health-based socio-economic assessment of drinking water quality: The case of Lebanon. *Management of Environmental Quality: An International Journal*, *14*(3), 353–368.

Etikan, I. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1.

García-Valiñas, M. A., Martínez-Espiñeira, R., & González-Gómez, F. (2010b). Affordability of residential water tariffs: Alternative measurement and explanatory factors in southern Spain -b. *Journal of Environmental Management*, *91*(12), 2696–2706.

García-Valiñas, M. D. L. Á., Martínez-Espiñeira, R., & González-Gómez, F. (2010a). Measuring Water Affordability: A Proposal for Urban Centres in Developed Countries -a. *International Journal of Water Resources Development*, *26*(3), 441–458.

Gleick, P. H. (1996). Basic Water Requirements for Human Activities: Meeting Basic Needs. *Water International*, *21*(2), 83–92.

Goddard, J. J. (2019). *Measuring Drinking Water Affordability and Sustainability*. University of California, Berkeley.

Goedemé, T., & Vanhille, J. (2018). Water expenses by households living in Flanders: Data availability in the Belgian EU-SILC. *Data in Brief*, *20*, 1568–1572.

Haddad, S. (2002). The relevance of political trust in postwar Lebanon. *Citizenship Studies*, 6(2), 201-218.

Hutton, G. (2012). Monitoring "Affordability" of water and sanitation services after 2015: Review of global indicator options. 95.

InfoPro Research & Lebanon Opportunities (2016). *Median Range of Salaries - By Sector*. Lebanon Opportunities. http://www.opportunities.com.lb/Lebanon/Employment/EmplymentCenter_SALARIES.asp

Hart, K. (1973). Informal income opportunities and urban employment in Ghana. *The journal of modern African studies*, 11(01), 61-89.

Jaafar, H., Ahmad, F., Holtmeier, L., & King-Okumu, C. (2020). Refugees, water balance, and water stress: Lessons learned from Lebanon. *Ambio*, *49*(6), 1179-1193.

Jepson, W., Budds, J., Eichelberger, L., Harris, L., Norman, E., O'Reilly, K., ... & Stoler, J. (2017a). Advancing human capabilities for water security: a relational approach. *Water Security*, 1, 46-52.

Jepson, W., & Vandewalle, E. (2016). Household water insecurity in the global north: a study of rural and periurban settlements on the Texas–Mexico Border. *The Professional Geographer*, *68*(1), 66-81.

Jepson, W. E., Wutich, A., Colllins, S. M., Boateng, G. O., & Young, S. L. (2017b). Progress in household water insecurity metrics: a cross-disciplinary approach. *Wiley Interdisciplinary Reviews: Water*, 4(3), e1214.

Komarulzaman, A. (2017). *Water affordability, water quality and their consequences for health and education in Indonesia* (Doctoral dissertation, Radboud Repository of the Radboud University, Nijmegen, the Netherlands).

Kooy, M. (2014). Developing Informality: The Production of Jakarta's Urban Waterscape. *Water Alternatives*, 7(1).

Liddle, E. S., Mager, S. M., and Nel, E. L. (2016). The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *The Geographical Journal*, 182(1), 85–96.

Mack, E. A., & Wrase, S. (2017). A Burgeoning Crisis? A Nationwide Assessment of the Geography of Water Affordability in the United States. *PLOS ONE*, *12*(1), e0169488.

Martins, R., Quintal, C., & Antunes, M. (2019). Making ends meet: Actual versus potential joint affordability of utility services. *Utilities Policy*, *56*, 120–126.

Meehan, K., Jepson, W., Harris, L. M., Wutich, A., Beresford, M., Fencl, A., ... & Young, S. (2020). Exposing the myths of household water insecurity in the global north: A critical review. *Wiley Interdisciplinary Reviews: Water*, *7*(6), e1486.

Maison des Français de l'Etranger (MFE) (2021, July, 30). *Marché du travail.* https://web.archive.org/web/20130713051102/http://www.mfe.org/index.php/Portails-Pays/Liban/Emploi-stage/Marche-du-travail

Ministry of Energy and Water (MoEW). (2010). National Water Sector Strategy. Retrieved from: http://www. databank.com.lb/docs/National%20Water%20 Sector%20Strategy%202010-2020.pdf

Ministry of Public Health (MOPH) (2020, May 13). *List of Bottled Water Permitted by MOPH*. Retrieved from https://www.moph.gov.lb/en/Pages/4/3365/list-of-bottled-water-permitted-by-moph

Moore, E., Matalon, E., Pacific Institute (Oakland, Calif.), Community Water Center, Clean Water Fund (Washington, D. C.), & California Rural Legal Assistance Foundation. (2011). *The human costs of nitrate-contaminated drinking water in the San Joaquin Valley*. Pacific Institute. http://www.pacinst.org/reports/nitrate_contamination/nitrate_contamination.pdf

Moser, C. O. (1978). Informal sector or petty commodity production: dualism or dependence in urban development?. *World development*, *6*(9-10), 1041-1064.

Nastiti, A., Sudradjat, A., Geerling, G. W., Smits, A. J. M., Roosmini, D., & Muntalif, B. S. (2017). The effect of physical accessibility and service level of water supply on economic accessibility: A case study of Bandung City, Indonesia. *Water International*, *42*(7), 831–851.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., & Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, *44*, 358–366.

Onda, K., LoBuglio, J., & Bartram, J. (2012). Global Access to Safe Water: Accounting for Water Quality and the Resulting Impact on MDG Progress. *International Journal of Environmental Research and Public Health*, *9*(3), 880–894.

Pattanayak, S. K., Yang, J.-C., Whittington, D., & Bal Kumar, K. C. (2005). Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal: COPING WITH UNRELIABLE PUBLIC WATER SUPPLIES. *Water Resources Research*, *41*(2).

Peloso, M., & Morinville, C. (2014). 'Chasing for Water': Everyday Practices of Water Access in Peri-Urban Ashaiman, Ghana. *Water Alternatives*, 7(1).

Ranganathan, M. (2014). 'Mafias' in the waterscape: Urban informality and everyday public authority in Bangalore. *Water Alternatives*, 7(1).

Revell, K. (2010, September). Working with informality: increasing resilience in cities of the Global South. In *46th ISOCARP Congress* (pp. 1-13).

Rosenberg, D. E., Tarawneh, T., Abdel-Khaleq, R., & Lund, J. R. (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research*, 43(7).

Salary Explorer. (February 2020). *Average Salary in Lebanon 2020.* http://www.salaryexplorer.com/salary-survey.php?loc=119&loctype=1

Satterthwaite, D. (2016). Missing the Millennium Development Goal targets for water and sanitation in urban areas. *Environment and Urbanization*, *28*(1), 99–118.

Sawkins, J. W., & Dickie, V. A. (2005). Affordability of Household Water and Sewerage Services in Great Britain*. *Fiscal Studies*, *26*(2), 225–244.

Sebri, M. (2015). Water affordability and social equity in Tunisian governorates: A distributive approach. *Water Policy*, *17*(1), 26–45.

Shaban, A. (2020). *Water resources of Lebanon*. Springer International Publishing.

Schwartz, K., Tutusaus Luque, M., Rusca, M., & Ahlers, R. (2015). (In) formality: the meshwork of water service provisioning. *Wiley Interdisciplinary Reviews: Water*, *2*(1), 31-36.

Smets, H. (2009). Access to drinking water at an affordable price In developing countries. 13.

Smets, H. (2012) Quantifying the affordability standard, in The Human Right to Water: Theory, Practice and Prospects. Cambridge University Press.

Teodoro, M. P. (2005). Measuring Fairness: Assessing the equity of municipal water rates. *Journal - American Water Works Association*, *97*(4), 111–124.

Teodoro, M. P. (2018). Measuring Household Affordability for Water and Sewer Utilities: Measuring Household Affordability for Water and Sewer Utilities. *Journal - American Water Works Association*, *110*(1), 13–24.

Thompson, J. et al., (2001). *Drawers of water II: 30 years of change in domestic water use & environmental health in east Africa. Summary* (Vol. 3). International Institute for Environment and Development.

UNICEF & WHO. (2006). *Meeting the Drinking Water and Sanitation Target*. New York: UNICEF & WHO.

United Nations (UN). (2020). *Sustainable Development Goals 6*. https://sustainabledevelopment.un.org/sdg6

UN Committee on Economic, Social and Cultural Rights (CESCR), *General Comment No. 15: The Right to Water (Arts. 11 and 12 of the Covenant)*, 20 January 2003, E/C.12/2002/11, available at: https://www.refworld.org/docid/4538838d11.html

Vanhille, J., Goedemé, T., Penne, T., Van Thielen, L., & Storms, B. (2018). Measuring water affordability in developed economies. The added value of a needs-based approach. *Journal of Environmental Management, 217,* 611–620.

Wada, Y., Van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., & Bierkens, M. F. (2011). Global monthly water stress: 2. Water demand and severity of water stress. *Water Resources Research*, *47*(7).

Walter, C. T., Kooy, M., & Prabaharyaka, I. (2017). The role of bottled drinking water in achieving SDG 6.1: An analysis of affordability and equity from Jakarta, Indonesia. *Journal of Water, Sanitation and Hygiene for Development*, 7(4), 642-650.

White, G., et al., (2002). Drawers of water: assessing domestic water use in Africa: public health classics. *Bulletin of the World Health Organization: the International Journal of Public Health 2002; 80 (1): 63-73*

WHO/UNICEF JMP. (2017). *Progress on drinking water, sanitation and hygiene: 2017update and SDG baselines* (Geneva) Online: http://www.who.int/iris/handle/10665/258617

Wutich, A., Budds, J., Eichelberger, L., Geere, J., Harris, L. M., Horney, J. A., ... & Shah, S. H. (2017). Advancing methods for research on household water insecurity: studying entitlements and capabilities, socio-cultural dynamics, and political processes, institutions and governance. *Water security*, 2, 1-10.

Young, S. L., Collins, S. M., Boateng, G. O., Neilands, T. B., Jamaluddine, Z., Miller, J. D., ... & Schuster, R. C. (2019). Development and validation protocol for an instrument to measure household water insecurity across cultures and ecologies: the Household Water InSecurity Experiences (HWISE) Scale. *BMJ open*, 9(1), bmjopen-2018.

Zaatari, A. (2019). *Housing production in uneven urban quarters: two case studies from Beirut (Lebanon) Aicha Bakkar and Tallet El Khayyat* (Unpublished master's thesis). American University of Beirut, Lebanon

Zawahri, N., Sowers, J., & Weinthal, E. (2011). The Politics of Assessment: Water and Sanitation MDGs in the Middle East: Water and Sanitation MDGs in the Middle East. *Development and Change*, *42*(5), 1153–1178.

Chapter 3: Water-Energy Nexus of Formal and Informal Water Systems in Beirut, Lebanon

Abstract

Many areas in the world with chronic and intermittent water shortages rely on informal water sources, such as water deliveries from water tanker trucks, purchase of bottled water, rainwater cisterns, or pumping water from local wells. These alternative sources all require energy inputs, and use varying amounts of energy to deliver water from source to consumer. Water-energy nexus studies have not yet considered environmental impacts of informal water sources from an energy intensity and carbon emissions perspective.

This study takes a Lebanese neighborhood as a case study and compares energy use and carbon emissions per cubic meter and per capita for both formal and informal water sources. Energy use and carbon emissions are calculated for three delivery stages per source including pumping, treatment and distribution.

The results show informal sources have high energy use and carbon emissions. They represent 99% of energy use and 97% of carbon emissions per cubic meter of water. They also account for 80% of total energy use and 69% of total carbon emissions per capita, even though they only provide 23% of total delivered volume per person per year. Other findings show that transporting water through trucks is highly inefficient and that internal building water pumping, which is not typically accounted for, is up to 14% of total energy use and 22% of total carbon emissions per capita.

Multiple strategies are proposed to improve the environmental performance of the Lebanese electrical grid, reduce water losses, replace inefficient truck engines and incentivize household to invest in low carbon technologies.

Introduction

The interdependence between water and energy is referred to as the water-energy nexus: energy is needed in water systems (Spang & Loge, 2015; Hamiche et al. 2016) and water is needed for energy and electricity production (Spang et al. 2020). Water-energy nexus field evolved from understanding the economic impacts of energy costs of water systems, to analyzing other technological and environmental dimensions of energy on water systems. This introduction highlights the development of the water-energy nexus field with some of its gaps, introduces the literature on informal water systems and ends with the study's focus and research question.

Earlier nexus studies, from the mid-1990s and early 2000s, focused solely on the economic impact of energy and water systems. For example, Hansen (1996) shows impacts of energy prices on residential water demand in Copenhagen by identifying a significant negative energy cross-price elasticity on residential water demand. deMonsaber and Liner (1998) focus on residential energy and water uses and develop integrated energy and water conservation models to identify water conservation options with payback periods of less than 10 years for one specific building. Schuck and Green (2002) focus on water prices for irrigation. They show that inter-seasonal variation in price can conserve both water and energy, and that the nexus of resources can reduce their price variability resulting in improved groundwater overdraft.

Environmental uncertainties, such as resource supply crises and growing scarcities (Al-Saidi & Elagib, 2017), show the need to move beyond economic impacts of energy on water systems and to reconsider how resources are consumed and managed. To propose more integrated and sustainable solutions, scholars and engineers started considering the interdependence of both water and energy and proposing strategies to save energy and lower overall water demand simultaneously (Dai et al. 2018).

Today’s energy-water nexus field has evolved into a range of more refined methods that highlight the importance of regional and local scales (King and Carbajales-Dale, 2016) and consider different environmental dimensions of energy within water systems (Spang et al 2020). Scott et al (2011) show the importance of integrating national and regional scales when managing water and energy resources. They explain that when permitting happens at federal and state agencies, local authorities are obstructed from managing their own local resources, resulting in a mismatch between energy and water resource linkages and regional waste and pollution (often unaccounted for as “environmental externalities”). Their paper proposes a multi-tiered institutional arrangement to improve resource governance. Fang et al (2015) estimate energy and emissions intensity of water supply of two utilities in Southern California and point out the importance of upstream emissions. Also, by using a spatially explicit Life Cycle Assessment (LCA) model they estimate emissions improvements for local utilities from renewable sources (instead of coal-based electricity). Spang & Loge (2015) develop a high resolution spatially explicit method by using granular hourly pumping regional data, and by integrating geographic and seasonal variations. Their method helps in developing more targeted and site-specific conservation measures that improve water and energy use. Mahgoub et al (2010) develop a Life Cycle Assessment (LCA) of Alexandria’s urban water system to determine its environmental impact and propose multiple scenarios to improve the system’s overall performance. Some studies focus on the environmental impacts of specific water sources only. For example, Gleick & Cooley (2009) focus on bottled water and develop energy footprint required for the various phases of producing, transporting and using bottled water. Stokes & Horvath (2006, 2009), compare energy use and air emissions of three supply alternatives of importing, recycling and desalinating water in California.

Even though nexus studies have a wide range of dimensions and objectives, they all focus solely on centralized formal piped water services (Hamiche et al. 2016). However, many areas experience chronic water shortages where piped centralized formal systems cannot supply sufficient water to residents (Liddle, 2014; Kooy, 2014; Misra, 2014; Jepson & Vandewalle, 2016). Around 30 to 60% of people in lower and middle income areas rely on informal water systems to satisfy their water needs (Ahlers et al. 2014). These systems can include different strategies for collecting, pumping, treating, and storing water (Pattanayak et al., 2005; Baquero et al., 2017; Nastiti et al., 2017; Amit and Sasidharan, 2019); or using alternative sources such as bottles, water tankers and wells (Moore et al., 2011; Christian-Smith et al., 2013; Nganyanyuka et al., 2014; Jepson & Vandewalle, 2016; Watler et al., 2017). These alternative and informal strategies use energy at different stages of their supply system including pumping, treating, and distributing water.

The literature on informal water systems has so far focused on analyzing political drivers and socio-economic implications of informal sources. For example, some studies looked at the complex governance aspect of managing multiple water sources including the relation and interdependencies between formal and informal water providers (Roy, 2005; Kudva, 2009; Ahlers et al., 2014; Schwartz et al., 2015; Liddle et al 2016). Others have quantified the socio-economic impacts of informality, either by assessing the added cost of informal sources (Pattanayak et al., 2005; Moore et al., 2011; Hutton 2012; Christian-Smith et al., 2013; Nganyanyuka et al., 2014; Baquero et al., 2017; Watler et al., 2017; Nastiti et al., 2017; Komarulzaman 2017; Amit and Sasidharan 2019); by analyzing the psychological distress of end-users that stems from water insecurity (Workman & Ureksoy 2017; Boateng et al, 2018; Young et al., 2019); as well as investigated health hazard impacts from water quality and waterborne diseases from unmonitored informal sources (El-Fadel et al., 2003; Kjellén & McGranahan, 2006; Constantine et al 2017). Few studies have focused on the environmental impacts of informality, especially the embedded energy of multiple informal water sources and associated carbon emissions.

Focus and the research question

This study analyzes the embedded energy of informal water systems. It quantifies energy use and carbon emission differences between formal and informal water systems. As a case study, we examine the Lebanese water system and compares the energy nexus and associated carbon emissions of three informal water sources (tankers, bottles, and domestic wells) with the formal piped infrastructure for a typical Lebanese neighborhood located in the capital, Beirut.

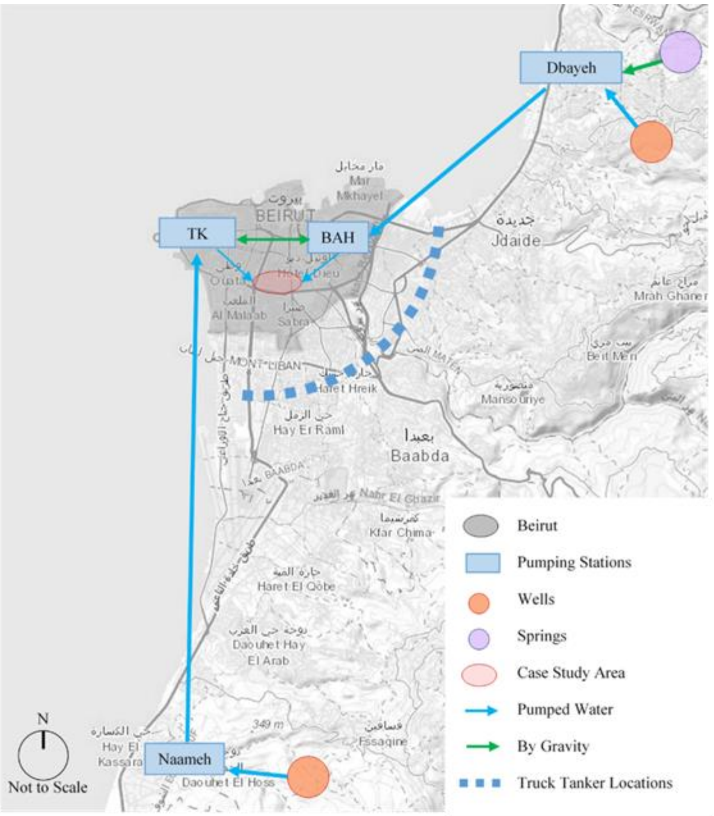
Energy use and carbon emission values are estimates for both formal and informal water systems in Beirut taking into consideration their different water delivery stages by source: pumping, treatment, and distribution of water. For each stage, energy use is calculated using key energy inputs (e.g. electricity to treat and pump water, and fuel to transport fresh and bottled water) instead of a single comprehensive life-cycle energy assessment (Gleick & Cooley, 2009). The analysis takes each source separately, and for each stage it calculates energy use and carbon emissions per cubic meter of water and total energy use and carbon emissions per capita.

Water Distribution and Energy Requirements

Water and energy at a regional level

Water is supplied to Beirut from two main areas, shown on **Map 5**. The main source is a northern water treatment plant in Dbayeh, which receives and treats water from two springs upstream and 17 additional wells. The plant supplies around 77% of the city's water use. The second largest water source (supplying 23% of total city water use) is groundwater from a cluster of 11 wells in the southern Naameh area that is chlorinated for disinfection. Water from these two locations is usually pumped to reservoirs in Beirut for storage before final residential delivery. The selected case region in this study is a typical neighborhood in Beirut (Verdun-Aicha Bakkar). It receives water from two main reservoirs, Tallet el Khayyat (TK) and Bourj Abi Haidar (BAH). Overall the water supply system experiences up to 45% of losses due to leakages in its distribution systems (Shaban, 2020; Bulos and Yam, 2021). The reservoirs cannot supply water on a 24/7 basis, so they pump water every 48 hours. Thus residents receive water for a continuous period of around 3 hours in the summer and around 7 hours in the winter each day.

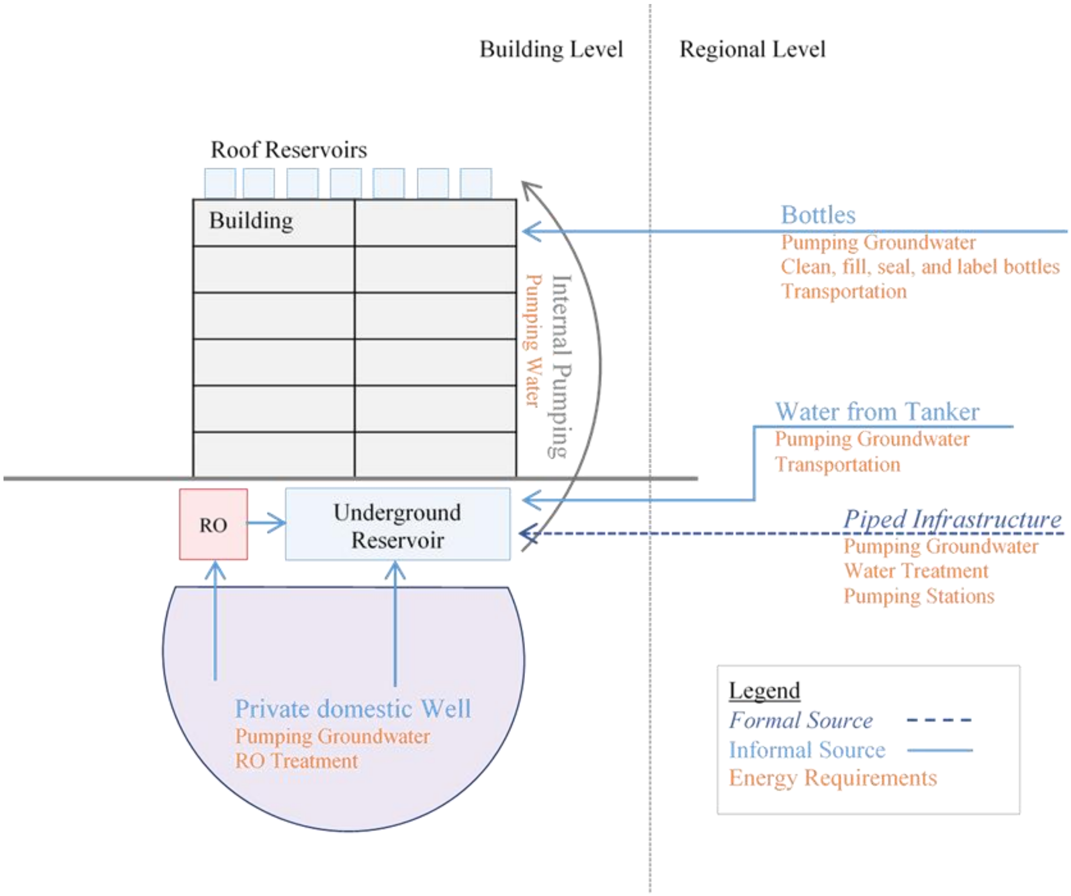
Map 5 – Schematic Water Distribution System in Beirut, Lebanon.



Water and energy at a building level

To cope with intermittence, residents in Beirut use various strategies. **Figure 9** shows typical paths for different water sources and their associated energy requirements (in italic). For freshwater, people commonly maintain on-site storage in underground and roof reservoirs to capture intermittent piped water from the municipal water supply. The piped water is first sent to underground tanks, which is usually a large reservoir shared by building residents (ranging from 10 m^3 to 80 m^3). Once the building reservoir is full, the water is then pumped to individual smaller roof tanks assigned to each apartment or household. When both underground and roof reservoirs empty, buildings and households seek other water sources, either pumping water from private wells (sometimes with additional treatment using reverse osmosis - RO) or buying water from water tanker trucks from the outskirts of the city. For potable needs, people rely mostly on bottled water, mainly because of distrust in the quality of delivered water (Zawahri et al., 2011). Bottled water companies usually draw water from the Lebanese Mountains where they pump, treat, and fill bottles. The bottles are then transported either directly to household or to local markets through regional delivery trucks.

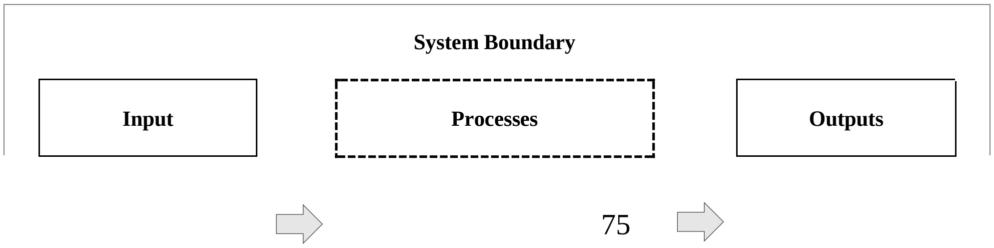
Figure 9 - Water and Energy at regional and building level.

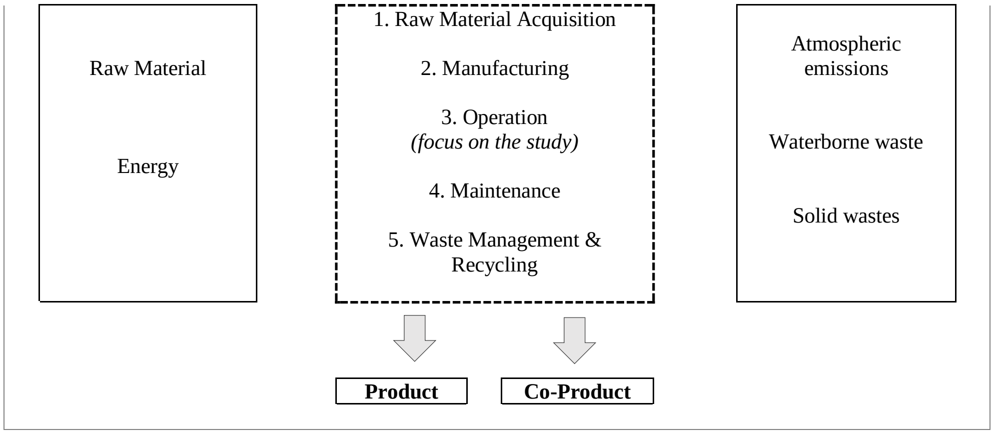


System boundary

Typical Life Cycle Assessment (LCA) studies for products have three main lifecycle phases including Inputs, Processes and Outputs as indicated in **Figure 10**. A product's system boundary is usually limited to the middle phase which can also produce co-products.

Figure 10 - Typical Life Cycle Phases (Based on EPA, 2006).





Even though we are not analyzing a product, the study is nevertheless organized by the boundary framework of LCA to analyze the energy-water nexus of multiple water sources. Using such a framework sets a holistic understanding of water sources and highlights the interconnectedness of different phases and processes. Similar to **Figure 10**, the Process Phase of the multiple water sources is also composed of 5 components, as indicated in **Table 16**. This includes the *acquisition of water* through drilling wells; the *manufacturing* of piped infrastructure, water treatment plants, trucks and bottles; the *operation* through different delivery stages, the *maintenance* of piped infrastructure, water treatment plants, trucks and cleaning of wells, and an *after-life* taking into account the dismantling of treatment plant, the *recycling* and reuse of trucks, and water bottles.

Table 16 - System Boundary and Contents

		Process Phase of Multiple Water Sources						
	Sources	**1. Raw Material**	**2. Manufacturing**	**3. Operation: Delivery Stages**			**4. Maintenance**	**5. After life/ Recycle**
				Pumping	**Treatment**	**Distribution**		
Regional level	**1. Formal Piped Infra-structure**	Drilling Well	Water treatment plant and infrastructure	Pumping Groundwater	Water Treatment	Pumping stations + Internal Pumping from lower to upper reservoirs	Maintenance of plant and infrastructure	Dismantling Treatment Plant

	2. Tanker Trucks	Drilling Well	Manufacturing and shipping of Trucks	Pumping Groundwater	NA	Transporting water through water trucks + Internal Pumping	Maintenance of trucks	Reusing and recycling truck and truck parts
	3. Bottles	Drilling Well	Processing bottles	Pumping Groundwater	Clean, fill, seal, and label bottles	Transporting water bottles through regional delivery trucks	NA	Reusing and recycling plastic bottles
Building level	**4. Private Domestic Wells**	Drilling Well	NA	Pumping Groundwater	Using RO to clean water	Internal Pumping	Cleaning well	NA

In LCA, systems boundaries usually focus on the Process Phase and can either take into consideration multiple stages or choose a specific one (Guinée and Heijungs, 2005). Our study focuses on the analysis of the Operation Stage of water systems by highlighting the delivery stage for different sources. As indicated in grey in **Table 16**, delivery stages include pumping, treatment, and distribution. The study examines the embedded energy of multiple sources. Delivery stages have different spatial scales (**Figure 9** and **Table 16**): formal piped infrastructure, tanker trucks, and bottles delivery stages operate at a regional level, and private wells operate at the building level. The water-energy nexus for each sources' stage is detailed below:

- Formal Piped Infrastructure: groundwater is pumped from Northern and Southern wells. Dbayeh water treatment plants treats surface water. Water (from north and south) is distributed through four pumping stations (refer to **Map 5**). Then at a building level, water is pumped from lower to upper reservoirs (refer to **Figure 9**).
- Tanker Trucks: groundwater is pumped and then delivered through trucks without any treatment. Similarly, at a building level water is then pumped internally.
- Bottles: groundwater is pumped, treated, bottled, and then transported through regional delivery trucks. Plastic production is not taken into account.

- Private wells: groundwater is pumped, and, for the buildings that can afford it, groundwater is treated with domestic reverse osmosis unites (RO). Then, at a building level water is pumped internally.

Data Collection

Data on energy use per volume of water was collected for each source following a mixed method approach, based on quantitative databases and interviews. Energy data on the formal piped infrastructure was provided by Beirut and Mount Lebanon Water Establishment and delivered volume data was derived from household interviews. Energy and water data on tanker trucks was derived from interviews with tanker truck owners. Energy and water data on private domestic wells and internal building pumping was based from household interviews. Whenever needed, supplementary information was employed based on feedback from water engineers from the water establishment and references from similar (international and local) cases. This was especially the case for water bottles. These references are elaborated further in the analysis section.

Quantitative Database on Energy requirements of Formal Piped Infrastructure

The Lebanese water establishment provided aggregated data on groundwater pumping, water treatment, and distribution.

Groundwater values based on northern and southern wells:

- Southern wells (with 11 pumps): nameplate capacity of pumps, and daily operation hours from April 2017 until July 2020.
- Northern wells (with 17 pumps): nameplate capacity of pumps with average operation hours.

Treatment values based on Dbayeh water treatment plant:

- Lump sum values of total volume treated per day.
- Energy intensity of treatment was not provided by the water establishment and thus based on Plappally & Lienhard (2012).

Distribution values based on pumping stations:

- Four pumping stations (Naameh with 6 pumps, Tallet el Khayat with 4 pumps, Dbayeh Station with 22 pumps, and Bourj Abi Haidar with 8 pumps): nameplate capacity of pumps, and daily operation hours from January 2018 until June 2018.

Additional information was also provided, by the water establishment, on typical pumps size used by tanker trucks, bottles, and households.

Tanker Interviews

Data on tanker trucks were collected via in-person interviews with truck owners in and around Beirut, over two-months from August 2019 to September 2019. A total of 20 interviews were conducted. The interviews were with the main manager or owner of the tanker truck business. Questions were asked in Arabic and all answers were collected in written notes by the researcher. The interviews followed an interview guide composed of different topic areas including water sources details, truck details, and socio-economic details (i.e. cost of service, communication with other business owners). The answers provided pumping groundwater and transportation details including:

- Average hours of groundwater pumping.
- Make/model, age, average volume carried, and average distance travelled of tanker trucks.

Household Interviews

Data on household water consumption and expenditures were collected by in-person household interviews in the Aicha Bakkar and Verdun communities over two-months from October to November 2019. We conducted 105 interviews, with at least one adult from each surveyed household. Multiple languages were used: the questions were mainly asked in Arabic and when necessary (especially when using some technical terms) the interviewer asked the questions in French and/or English. The answers were collected using the Survey123 phone application from ESRI ArcGIS. The interviews followed an interview guide of different topic areas including the urban typology of the building (such as building location and age, number of floors, and number of apartments), socio-economic details about the residents, and details of different water sources.

The first set of answers provided details on groundwater pumping, water treatment and distribution:

- The operation hours of private wells and their pumped volume.
- The operation hours of domestic reverse osmosis units.
- The operation hours of additional internal pumps and their volume.

The second set of answers provided details on delivered volumes from different sources per day:

- The volume of water deliveries by type of water source, temporal delivery of sources (frequency of delivery), scale of delivery (i.e. is water delivered for the building or the household), and seasonal variations.

Tanker truck and household interviewees were recruited with a convenience sampling process. Interviewees were recruited based on ease of accessibility, willingness to participate, and geographic location in the two communities (Etikan, 2016). Random sampling was not possible at the time given the political instability during the data collection period. The sampling process started with one main contact (per tanker truck and per community). At the end of each interview, the interviewees would share contact information for other tanker truck business owners (for the tanker trucks interviews), or other social connections located in the neighborhood, including their neighbors (for the household interviews). The researcher would then contact by phone the new names to make appointments. For the tanker trucks, the process was repeated until the direct contact list was exhausted, where no new tanker truck was answering the phone for new appointments. As for the household, the process was repeated until the sample size of 105 was reached (for the households with 52 in Aicha Bakkar and 53 in Verdun). The sample size was based on sample sizes used in other studies in the fields of informal water systems, and meets minimum standards for valid statistical analysis given the political and financial constraints (Rosenberg et al., 2007; Jepson & Vandewalle, 2016; Walter et al., 2017).

Data Analysis

The analysis starts with intensive energy and carbon emissions per cubic meter of water per delivery stage. The unit of analysis is kilowatt hour per cubic meter of water (energy intensity (EI)= kWh/m^3), and kilogram of carbon dioxide per cubic meter of water (carbon intensity (CI)= kg CO_2/m^3). Per capita energy use and carbon emissions for the neighborhood are then calculated by multiplying EI and CI results by total delivered volumes per source per person per year. The unit of analysis is total kWh per person per year (E=kWh/person/year) and total kilogram of carbon dioxide per person per year (C=kg CO_2/m^3/person/year).

Intensive Energy Use and Carbon Emissions per Cubic Meter of Water

As highlighted in **Table 17**, water delivery stages rely on three main activities: pumping (blue), treating (green), and transporting water (pink). General formulas are used for same activities (irrespective of source):

<u>Pumping (blue):</u> energy to pump water, including groundwater, pumping stations and internal building-level pumping. Any energy used for pumping from tanker trucks to buildings is neglected given that trucks generally empty their tanks by gravity to lower building reservoirs.

<u>Treatment (green):</u> energy to treat raw water sources, including water treatment plant, domestic reverse osmosis units and energy to clean, fill, seal, and label bottles.

For these two stages, pumps are assumed to use electricity from the Lebanese electrical grid with a carbon intensity of 0.774 kg of CO_2/kWh (IEA, 2019). Energy use per volume EI (kWh/m^3) and carbon emission per volume CI (kg of CO_2/m^3) are calculated as:

EI (kWh/m^3)[3] = Energy Use (kWh) / Pumped or Treated Volume (m^3)

CI (kg of CO_2/m^3)[4] = EI x Carbon Intensity of the Grid (kg of CO_2/kWh)

<u>Transportation (pink):</u> fuel needed to transport water through two truck types, water tankers transporting bulk water and regional delivery trucks for bottled water. Energy use per transported volume ET (kWh/m^3) and carbon emissions per transported volume CT (kg of CO_2/m^3) are calculated as:

EIT (kWh/m^3) = Fuel Economy (Liter of Diesel/100Km) x

Energy Content of Diesel (kWh/m^3 of Diesel) x

Distance (km) / Truck Volume (m^3) /100

CIT (kg of CO_2/m^3) = ET x Emissions Factor (kg CO_2/Liter of Diesel)

Fuel Economy is based on European references for fuel economy of trucks since most trucks in Lebanon come from European markets (MoE/UNDP/GEF, 2019). We used average weight of both trucks types and compared them with European trucks of similar weights to derive fuel economy values. Energy content of diesel is equal to 34.8 MJ per Liter of diesel. Distances are equal to travelled distance from well to neighborhood for each truck type. Volumes are average volume of each truck type, based on interviews and payload weight of trucks. Emission Factors are based on the tier 1 method by the IPPC (2006) with CO_2 emissions from a liter of diesel equal to 2.7 kg CO_2 per liter of diesel.

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[3] Reference in **Table 17:**

EI_p= Energy intensity for pumping

EI_t= Energy intensity for treatment

EI_d= Energy intensity for distribution

[4] Reference in **Table 17:**

CI_p= Carbon intensity for pumping

CI_t= Carbon intensity for treatment

CI_d= Carbon intensity for distribution

Carbon intensity of Lebanese electrical grid (kg CO_2/kWh) and emission factors for diesel (kg CO_2/Liter of diesel) represent carbon emissions from combustion only. This means that for the electrical grid this represents carbon emissions from the combustion of fossil fuel for electricity generation, and for trucks it is carbon emissions from combustion of diesel for engines (IEA, 2019; IPCC, 2006).

General equations and values of each source and stage are included in **Table 17.** Step by step calculations are in **Appendix I**.

Table 17 – General Equations and Values per Source and Stage

Sources	**Delivery Stages**		
	Pumping	**Treatment**	**Distribution**
***** **Formal Piped Infra-structure**	**Pumping Groundwater** **EI_p**= 442 (kWh) / 3,220 (m^3) **CI_p**= EV x 0.774 (kg of CO_2/ kWh) • Nameplate hydraulic power[1]: 68 kW • Nameplate pumping capacity[1]: 3,220 m^3/Day • Operating hours[1]: 6.5h/Day • Electrical consumption: 442 kWh/Day	**Water Treatment** **EI_t**= 0.56 (kWh/m^3) **CI_t**= EV x 0.774 (kg of CO_2/ kWh) • Energy Use per volume[2]: 0.56 kWh/m^3 • Treated volume[1]: 200,000m^3/Day	**Pumping stations** **EI_d**= 11,275 (kWh) / 81,190 (m3) **CI_d**= EV x 0.774 (kg of CO2/ kWh) • Nameplate hydraulic power[1]: 505 kW • Nameplate pumping capacity[1]: 81,190 m^3/Day • Operating hours[1]: 22h/Day • Electrical consumption: 11,275 kWh/Day + **Pumping Water: Lower to Upper Reservoirs** (Equation and Values below)
****** **Tanker Trucks**	**Pumping Groundwater** **EI_p**= 396 (kWh) / 183 (m3) **CI_p** = EV x 0.774 (kg of CO_2/ kWh) • Hydraulic power[1]: 67 kW • Pumping capacity[3]: 183 m^3/Day • Average operating hours[3]: 6h/Day • Average electrical consumption: 396 kWh	NA	**Transporting: Water Trucks** **EIT=** 33.1 (L of fuel/ 100 km) x 34.8 (MJ/L of fuel) x 40 (km) / 19 (m3)/100 **CIT=** ET x 2.7 (kg CO2/L of diesel) • Fuel economy[4]: 33.1 L of fuel/ 100 km • Travelled Distance[3]: 40 km (round-trip). • Truck Volume[3]: 19 m^3 Payload Weight: 19 tons + **Pumping Water: Lower to Upper Reservoirs** (Equation and Values below)
****Bottles**	**Pumping Groundwater** **EI_p**= 1,604 (kWh) / 2,055 (m^3) **CI_p** = EV x 0.774 (kg of CO_2/ kWh) • Hydraulic power[1]: 67 kW • Operating hours of pumps[1]: 24 h/Day • Pumping capacity[5]: 2,055 m^3/Day • Electrical consumption: 1,604 kWh	**Clean, fill, seal, and label bottles** **EI_t** = 0.92 (kWh/m^3) **CI_t** = EV x 0.774 (kg of CO_2/ kWh) • Energy Use per Volume[6]: 0.92 kWh/m^3	**Transporting: Regional Delivery Trucks** **EIT=** 36.4 (L of fuel/ 100 km) x 34.8 (MJ/L of fuel) x 200 (km) / 12 (m3) / 100 **CIT=** ET x 2.7 (kg CO2/L of diesel) • Fuel economy[4]: 36.37 L of fuel/ 100 km • Travelled Distance[7]: 200 km (round-trip). • Truck Volume[4]: 12 m^3 • Payload Weight: 12 tons

Private Domestic Wells	**Pumping Groundwater** **EI_p**= 0.011 (kWh) / 0.018 (m^3) **CI_p** = EV x 0.774 (kg of CO_2/ kWh) • Hydraulic Power[1]: 0.745 kW • Hours of Operation[8]: 0.014 h/Day • Pumped volume[8]: 0.018m^3/Day • Electrical consumption: 0.011 kWh/Day	**Using RO to clean water** **EI_t** = 0.5 (kWh/m^3) **CI_t** = EV x 0.774 (kg of CO2/ kWh) • Energy Use per Volume[6]: 0.5 kWh/m^3	**Pumping Water: Lower to Upper Reservoirs** (Equation and Values below)

In addition to the energy use and carbon emission of the four sources in the above table**,** we calculate the internal pumping separately since the volume that is pumped from lower to upper reservoir is a mixture of three sources (piped infrastructure, tanker trucks and private domestic wells, refer to **Figure 9)**. This is based on:

EI_d = 0.058 (kWh) / 0.652 (m^3)

CI_d = EV x 0.774 (kg of CO_2/ kWh)

• Hydraulic Power[1]: 0.745 kW

• Hours of Operation[8]: 0.078 h/Day

• Pumped volume[8]: 0.652m^3/Day

• Electrical consumption: 0.058 kWh/Day

[1] Beirut and Mount Lebanon Water Establishment.

[2] Margan & Houben, (2010) and Plappally & Lienhard (2012).

[3] Tanker Truck Survey.

[4] Rodríguez et al (2018) and Delgado et al (2017).

[5] Daou & Mikhael (2016).

[6] Gleick & Cooley (2009).

[7] Average roundtrip distance from two major springs in Mount Lebanon – Sohat and Sannine – to neighborhood including traffic.

[8] Household Survey.

* Energy of Formal Piped Infrastructure: Groundwater pumping and Distribution take into account weighted averages of wells: 77% Northern wells and 23% Southern wells.

**Transportations: takes into consideration payload weight of trucks.

Total Supplied Volume by Source & Total Energy Use and Carbon Emissions per Capita

Total energy use and carbon emissions per person per year are calculated by multiplying energy intensity and carbon emissions per total delivered volumes for all water sources. Total delivered volumes per sources are based on Chapter 2. For each source, volume unit conversion calculations provide total supplied cubic meter per person per year (m^3/person/year).

Table 18 - Delivered Volumes per Source per Person per Year (m^3/person/year) (based on Chapter 2)

Water Sources	**Case Study Area: Estimated Delivered Volumes per Person per Year** m^3/Person/Year
Formal Piped Infrastructure	35.6
Tanker Trucks	4.7
Bottles	0.8
Private Domestic Wells	5.4
+ Internal Building Pumping *	238

* This water is internally pumped from lower to upper reservoir, after storage.

Results

The results are divided into two: intensive energy use and carbon emissions per cubic meter of water per source for different delivery stages; and total energy use and carbon emissions per total delivered volumes per source per person per year for the case study area.

Intensive Energy Use per Cubic Meter

Table 19 – Intensive Energy Use per Cubic Meter of Water per Stage and Source (kWh/m^3)

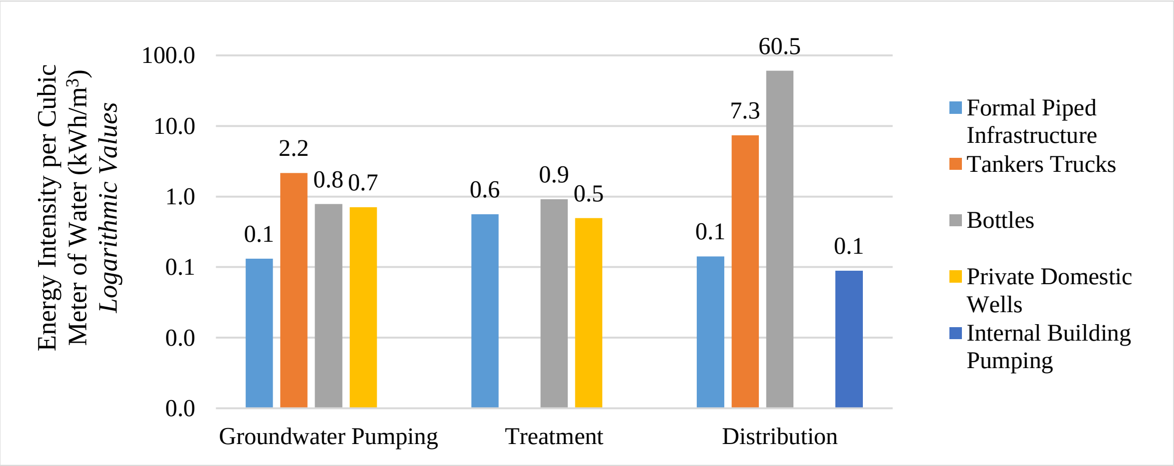
Energy Intensity kWh/m^3	**Ground Water Pumping**	**Water Treatment**	**Distribution**	**Total Energy Intensity**
Formal Piped Infrastructure	0.1	0.6	0.1	0.8
Tankers Trucks	2.2	NA	7.3	9.5

Bottles	0.8	0.9	60.5	62.2
Private Domestic Wells	0.7	0.5	NA	1.2
+ Internal Building Pumping	NA	NA	0.1	0.1

The energy use intensity per cubic meter for the groundwater pumping is divided as following: tanker trucks have the highest energy intensity 2.2 kWh/m^3, followed by bottles 0.8 kWh/m^3, private domestic wells 0.7 kWh/m^3, and the formal piped infrastructure 0.1 kWh/m^3. For the treatment, the energy use intensity is highest for bottles with 0.9 kWh/m^3, followed by the formal piped infrastructure 0.6 kWh/m^3 and then private domestic wells 0.5 kWh/m^3. For the distribution, the energy use intensity is also highest for bottles with 60.5 kWh/m^3, followed by tankers trucks 7.3 kWh/m^3, and the formal piped infrastructure 0.1 kWh/m^3.

Informal sources' total energy use intensity is high compared to the piped infrastructure, composed of bottles with 62.2 kWh/m^3, tanker trucks with 9.5 kWh/m^3, private domestic wells with 1.2 kWh/m^3, and internal building pumping is almost insignificant with 0.1 kWh/m^3. The formal piped infrastructure total energy use is 0.8 kWh/m^3.

Figure 11 - Intensive Energy Use per Cubic Meter of Water per Stage (Logarithmic Values - kWh/m^3)



Intensive Carbon Emissions per Cubic Meter

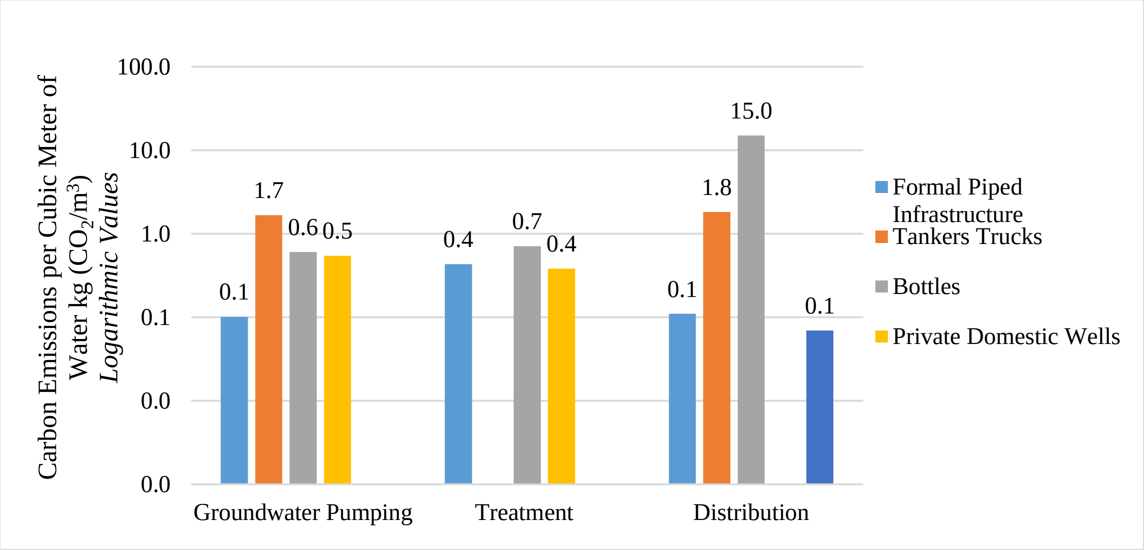
Table 20 - Intensive Carbon Emissions per Cubic Meter of Water per Stage and Sources (kg of CO_2 /m^3)

Carbon Emissions kg of CO_2 /m^3	**Pumping Groundwater**	**Water Treatment**	**Distribution**	**Total Carbon Emissions**
Formal Piped Infrastructure	0.1	0.4	0.1	0.6
Tankers Trucks	1.7	NA	1.8	3.5
Bottles	0.6	0.7	15	16.3
Private Domestic Wells	0.5	0.4	NA	0.9
+ Internal Building Pumping	NA	NA	0.1	0.1

The carbon emissions intensity per cubic meter for groundwater pumping is divided as follows: tanker trucks have the highest carbon emissions 1.7 kg CO_2/m^3, followed by bottles 0.6 kg CO_2/m^3, private domestic wells 0.5 kg CO_2/m^3, and formal piped infrastructure 0.1 kg CO_2/m^3. For treatment, the carbon emissions intensity is highest for bottles with 0.7 kg CO_2/m^3, followed by both formal piped infrastructure and private domestic wells, both equal to 0.4 kg CO_2/m^3. For distributions, the carbon emissions intensity is also highest for bottles with 15 kg CO_2/m^3, followed by the tankers 1.8 kg CO_2/m^3 and then the formal piped infrastructure 0.1 kg CO_2/m^3.

Informal sources' total carbon emission intensity is high compared to the piped infrastructure, with bottles at 16.3 kg CO_2/m^3, tanker trucks 3.5 kg CO_2/m^3, private domestic wells 0.9 kg CO_2/m^3, and the internal pumping releases insignificant amounts of CO_2 with 0.1 kg CO_2/m^3. The formal piped infrastructure has a total carbon emission intensity of 0.6 kg CO_2/m^3.

Figure 12 - Intensive Carbon Emissions per Cubic Meter of Water per Stage (Logarithmic Values - kg CO_2/m^3)



Total Energy Use and Carbon Emissions of Water per Capita

The formal piped infrastructure delivers roughly 36 m^3 person/year (77%) of the overall volume to the neighborhood with, followed by domestic wells which provide 5m^3/person/year (12%), tanker trucks with 4.7m^3/person/year (10%), and lastly bottles which provide 0.7m^3/person/year (2%). Since internal pumping is not a water source, its volume is not included in the total water volume.

Table 21 - Total Energy Use and Carbon Emissions per Person per Year

	Volume of Water Delivered per Person per Year m^3/Person/Year		Total Energy Use per Person per Year kWh/Person/Year		Total Carbon Emissions per person per Year kg of CO^2/Person/Year	
Formal Piped Infrastructure	35.6	77%	30	20%	23	31%
Tanker Trucks	4.7	10%	44	29%	16	22%
Bottles	0.7	2%	45	33%	12	18%
Private Domestic Wells	5.4	12%	6	4%	5	7%
Total Volume for all Sources	**46**	-	**147**	-	**73**	-
+ Internal Building Pumping	238		21	14%	16	22%

In terms of total energy use per person, bottled water has the highest total energy use with 45 kWh/person/year (33%), followed by tanker trucks with 44 kWh/Person/Year (29%), formal piped infrastructure with 30 kWh/Person/Year (20%), internal pumping 21 kWh/Person/Year (14%), and lastly private domestic wells with 6 kWh/Person/Year (4%). Bottles and tankers have the highest intensive energy use values per cubic meter 62 kWh/m^3 and 10 kWh/m^3 respectively (**Table 19**), which explains their high annual per capita energy use. Formal piped infrastructure has the highest delivered volume, which translates into high proportion of annual per capita energy use (even though it has one of the lowest intensive energy use per cubic meter value of all sources at 1 kWh/m^3, **Table 19**). Internal building pumping still has sizable energy use per capita, because of the high volume internally pumped. Finally, private wells have the lowest per capita energy use, given its low intensive energy use per cubic meter (1 kWh/m^3, **Table 19**) and its small share of volumetric water use.

For total carbon emissions per capita, formal piped infrastructure has the highest carbon emissions with 23 kg of CO_2/Person/Year (31%), followed by tanker trucks and internal pumping with 16 kg of CO_2/Person/Year (22%), bottles with 12 kg of CO_2/Person/Year (18%), and private domestic wells have the lowest percentage with 5 kg of CO_2/Person/Year (7%). High formal piped infrastructure carbon emissions can be linked to the inefficient Lebanese electrical grid, which is further elaborated in the discussion section. Tanker truck have the second highest carbon emissions mainly related to the inefficiency of the trucks (even with relatively a low supply of 4.7 m^3/Person/Year, **Table 21**). Internal pumping has relatively high carbon emissions, because of the high volume that is internally pumped (even though it has the lowest intensive carbon emissions per cubic meter with 0.1 kg of CO_2/m^3,**Table 20**). Bottles have a relatively low total carbon emissions because of their low delivered volume (even with the highest intensive emissions per cubic meter value with 16 kg of CO_2/m^3,**Table 20)**. As for private domestic well, their total emissions have the lowest percentage, because they have a low intensive carbon emissions per cubic meter value (1 kg CO_2/m^3, **Table 20**).

Discussion

Although nexus studies have evolved taking different technical, environmental and geographical dimensions into their analysis, they fall short in solely focusing on centralized formal piped water services (Hamiche et al. 2016). This study addresses this gap and is first in analyzing energy nexus of formal piped water sources and informal sources, including bottles, tanker trucks and private wells. Using a Lebanese neighborhood in Beirut as a case study, we compare energy use and carbon emissions per cubic meter and per capita for formal and informal water sources. Energy use and carbon emissions are calculated for three delivery stages per source including Pumping, Treatment and Distribution. Our main findings show the following: 1) informal water sources altogether have the highest energy use and carbon emissions. They represent 99% of energy use and 97% of carbon emissions per cubic meter of water. They also account for 80% of total energy use and 68% of total carbon emissions, even though they only provide 24% of total delivered volume per person per year. 2) Bottled water and distribution of water though tankers have the highest intensive energy use values per cubic meter of all water sources. 3) At the per capita level, the results reveal relatively high energy use and carbon emissions from pumping water internally and high carbon emissions values from the formal piped infrastructure system.

Intensive Energy Use and Carbon Emission per Cubic Meter

Sources

The results show that informal water sources have the highest energy use and carbon emissions values per cubic meter, with bottles having the highest values, from having the highest unit values for treatment and distribution. For treatment, this is expected since drinking water goes through greater filtration with higher energy use. However, because of absence of data on water treatment for bottled water companies in Lebanon, we used average energy values of typical treatment methods of ozonation, UV radiation, ultrafiltration, and reverse osmosis (with a TDS of 500ppm), based on Gleick and Cooley (2009). Without accurate data on treatment technologies in Lebanon, it is difficult to assess our results of 0.9 kWh/m^3

(**Table 19**), as energy intensity for water treatment can vary from 0.01 kWh/m^3 to 1.8 kWh/m^3, and might reach up to 3kWh/m^3, as in Southern California (Gleick and Cooley, 2009). For transportation, regional delivery trucks have an energy intensity 78% higher than tanker trucks because of their fuel economy, which is 36.4 L of fuel/100 km compared to tanker trucks with 33.1 L of fuel/100 km, and because they have 5 times the traveling distance (with 200 kilometers compared to 40 kilometers). This is aligned with findings by Gleick and Cooley (2009) which present three scenarios for transporting water and show that the shortest distance traveled by the least efficient mode of transportation is the least energy intensive.

Formal piped infrastructure system has low intensive energy use values per cubic meter, around 1% of energy use and 3% of carbon emissions per cubic meter of water. Even though we expected that piped infrastructure to be more efficient with lower energy use and carbon emissions values, the results seem a bit too low. Generally, when comparing our results to other studies in the literature, our values are slightly lower. The average energy intensity values per cubic meter of formal piped infrastructure of 20 examples from Africa, Asia, Europe, and North America, is around 1.4 kWh/m^3, (Lee et al, 2017) showing that the energy intensity of the Lebanese piped infrastructure is almost a third less (28% lower). This can be linked to limitations in data availability on groundwater pumping, treatment and distribution, which are discussed in the limitations section. Nevertheless, even if we increase the formal piped infrastructure results by 28%, informal sources still contribute most energy use and carbon emissions.

Delivery Stage

As expected, this case study shows water transportation through trucks (bulk water through tanker trucks and bottles through regional trucks) has the highest energy intensity and carbon emissions per cubic meter of water. Even though the results meet our expectation with trucks having higher emissions than pumping stations, we expect trucks to have even higher values. The calculations were based on average fuel economy for trucks, without accounting for truck age. Our interviews with water tankers showed trucks were made between 1970s and 2020s (with 40% made between 1970 and 1999 and 60% made between 2000 and 2020). Since older trucks are usually less efficient, we expect trucks in Lebanon have higher emissions than our estimates. In addition, tankers have additional harmful hidden emissions such as the NOx and other impacts from black carbon (BC) and particulate matter (PM) not included here. The main problem is that tankers usually operate inside a city, releasing these harmful emissions to populated areas. Further studies could include impacts of informal water supplies from NOx, BC, and PM on residents. Tankers have also other volume restrictions compared to formal piped infrastructure as they can only transport a limited volume with each trip. Thus, even though they are solutions to overcome water shortages, they still cannot replace the formal piped infrastructure.

Total Energy Use and Carbon Emissions Per capita Informal sources

When added together, the informal sources (tanker trucks, bottles and private domestic wells), represent 80% of total energy use and 68% of total carbon emissions, even though informal sources are 24% of the total water supply only. While we expected tankers and bottled water to have high energy use and carbon emissions (because of their high intensive values per cubic meter), we were surprised with the results from internal building pumping. Even though internal pumping has very low intensity per cubic meter values, it still contributes to 14% of per capita energy use and 22% of per capita carbon emissions mainly a result of the high pumped volumes from lower to upper reservoir. Internal pumping is not usually accounted for in nexus studies because it is not a typical infrastructure. However, this study shows that in areas of chronic water shortages, residents maximize their on-site storage using lower and upper reservoirs and need to pump their water internally at a building level. Our interview answers indicate that resident pump water internally around 10 hours per day.

Formal piped infrastructure

The formal piped infrastructure has 20% of per capita energy use, which is relatively low, and ranking third after bottles and tankers. This is mainly because of low intensity per cubic meter values, that are discussed earlier. However, contrary to our expectations, it has the highest per capita carbon emissions. These high carbon emissions values, can be linked to high delivered volumes of 77%, and also to the inefficient and carbon intensive Lebanese grid. Our calculations assume that to operate the formal water system, piped infrastructure use electricity from the Lebanese grid. The Lebanese grid has a carbon intensity 60% higher than world averages, with a value of 0.774 kg of CO_2/kWh as compared to the average world grid carbon intensity of roughly 0.485 CO_2/kWh (IEA, 2019). So this high carbon intensity values per cubic meter results in higher per capita carbon emissions for the piped water infrastructure.

Recommendations and implications

Since informal water sources have higher energy use and carbon emissions values than the formal water system in this case study, most recommendations focus on addressing informal water sources. Nevertheless, equally important is to address high total carbon emissions from the piped infrastructure, related to the inefficient Lebanese electrical grid. One way forward, would be to move away from relying heavily on fossil fuel, and to invest in and use renewable energy to improve the performance of the electrical grid and reduce overall formal infrastructure emissions.

Informal water sources often are needed to help communities access water and overcome water shortages. However, there is a trade-off for using them. Generally, they are 3 to 40 times more expensive (Wutich et al 2016), use more energy, and emit more carbon. To transition to a more resilient and sustainable system, we need strategies that reduce socio-economic and environmental impacts of informal sources or reduce the need for them. Knowing that the Lebanese water system suffers form 45% of losses because of leakages (Shaban 2020; Bulos and Yam, 2021), ideally solutions would first focus on improving formal piped infrastructure to reduce losses, which could eliminate demand for informal sources. This strategy is currently being developed by the Lebanese water utility as an indirect method to eliminate informal tankers (Hoayek, personal communication, September 8, 2019). By reducing water losses, the water utility hopes to supply more water to households and decrease demand for tankers. However, in areas that face mismanagement from governmental institutions coupled with poverty and corruption (Rogers & Hall, 2003), upgrading formal piped infrastructure is very challenging. So relying on hybrid strategies that do not eliminate informal sources, but rather attenuate their impacts, might be more realistic in the short term.

Informal sources have developed in different ways and at different scales, hence different strategies could address them. On a city scale, bottles and bulk water are usually transported by tanker trucks that tend to have high energy use and emissions levels. These trucks are owned by private companies. Hence to reduce their energy and emissions levels, policy recommendation could eliminate the use of old and polluting trucks with inefficient engines and push all truck owners to upgrade to more efficient engines. At a building level, Lebanese households rely on on-site storage and on private wells, which result with relatively high energy use and carbon emissions from pumping water internally. Internal pumping, happens usually in a decentralized way, within buildings and is controlled by residents themselves. Strategies could incentivize individuals of different socio-economic levels to move towards more efficient technologies. In Lebanon, a successful example has been the widespread adoption of solar water heaters (SWH) by households of different socio-economic levels. This was only possible through financial incentive programs that let individuals take loans at low interest rates and subsidies to install SWH, as long as they purchase the SWH from qualitied companies approved by the Lebanese Ministry of Energy and Water (LCEC, 2019). The financing mechanism was based on a collaboration between the Lebanese Central Bank, Lebanese local commercial banks and the Lebanese Ministry of Energy and Water (LCEC, 2019). Hence, intermediate strategies could try to readapt already-in-use solutions through similar financing mechanisms and encourage individuals to use more efficient household pumps or incentivize them to invest in other low carbon technologies, such as household solar water pumps. Decentralized solutions provides flexibility in infrastructure (Brown et al. 2009; Farrelly & Brown 2014; Bichai et al. 2015) and improve community cohesion through participation that drives community involvement and empowerment (Kyessi 2005; Russell 2014).

In Lebanon water shortages are widespread and communities of different socio-economic levels resort to informal water sources to satisfy their daily water needs. However, in other examples around the world, informal water systems tend to be more present among vulnerable and disadvantaged communities (Ranganathan, 2014; Peloso and Morinville, 2014; Jepson and Vandewalle, 2016; Balazs and Lubell, 2014; Balazs and Ray, 2014). Lower income communities tend to pay more for water, relative to their income (Teodoro, 2018). So we can expect those communities will pay more their water and energy. Some water disparity studies have looked the ability of low-income communities to pay for water while still being able to afford other essential costs such as housing, food, health care, and energy (Teodoro, 2018). Moving forward, further research is needed on informal water systems to understand how their energy nexus contributes to socio-economic disparities.

Limitations

Data availability was a limitation for different sources. For the piped infrastructure, we could not obtain actual energy intensity values for groundwater pumping and distribution, hence we used nameplate pump capacities that did not include efficiency factors of the pumps. Moreover, pump station data was limited to a six-month period, from January to June 2018. Hence, we could not account for seasonal changes. And for the treatment of piped infrastructure, we could not obtain energy data on the water treatment plant, we used energy intensity values per cubic meter based on estimates from Plappally and Lienhard (2012).

As for informal sources, to obtain energy and water data, we developed our own surveys. We used our own data gathered from 20 tankers and 100 household interviews, and, it was not possible to triangulate our own raw data as national statistics on household water use and water tanker use are not available. We could not obtain any energy and volume data on pumping groundwater for tankers and bottled water companies. Thus, we based our assumption on formal piped system values, which, as discussed above, seem to be less than other case studies. Moreover, we could not obtain data on water treatment for bottling companies in Lebanon and we based our calculations on Gleick and Cooley (2009), one of the rare studies that focuses on energy impacts of bottled water. We are aware that the study differs in scope and context therefore we followed typical treatment techniques applied in bottling plants and used the energy use values proposed by Gleick and Cooley (2009). Further studies are needed to validate pumping groundwater values and drinking water treatment values.

Conclusion

People in areas suffering from water shortages rely on alternative sources for water, including formal piped infrastructure and informal sources such as tanker trucks, bottled water, and wells. These informal sources are essential in securing community access to water, beyond inadequate supplies from formal piped water infrastructure. However, the water-energy nexus literature has so far omitted environmental impacts of informal water sources, specifically their energy use and carbon emissions. When 30% to 60% of communities worldwide rely on these informal sources (Ahlers et al. 2014), it becomes necessary to develop a framework that includes energy use and carbon emissions from multiple informal water sources. This study develops such a framework and compares the energy use and carbon emissions (both per cubic meter and per capita) for formal and informal water sources per cubic meter of water and per total delivered volume for the case study area of Aicha Bakkar and Verdun.

Overall findings show that informal water sources altogether have the highest energy use and carbon emissions. They are 99% of energy use and 97% of carbon emissions per cubic meter of water. They are also 80% of total energy use and 68% of total carbon emissions, even though they only provide 24% of total delivered volume per person per year. Even when communities barely rely on informal sources, their environmental impacts are still big. The study sheds light on other hidden energy use and carbon emissions from pumping within building. Such activities are not accounted for in typical energy-water nexus studies. Moreover, trucks are generally less efficient at different levels: they have the highest levels of energy use and carbon emissions, they have added emissions from NOx black carbon and particulate matter, and they can move much lower volume than pumping stations. Finally, even though formal piped infrastructure has the lowest impacts per cubic meter, it has the highest total carbon emissions values because of the inefficient Lebanese electric grid.

The study recognizes the role of informal sources in compensating for the inadequacy of supply from the formal piped infrastructure. It suggests the need to reduce losses from leakages of the formal system. It also proposes hybrid strategies to attenuate informal system’s impacts by replacing inefficient truck engines and by developing financial mechanisms that will incentive household to invest in solar water heater and other low carbon technologies.

The study is first to compare the energy-water nexus of formal and informal water sources, in highlighting the high energy use of informal sources and their high carbon emissions. Moving forward, it would be important to compare these results with other areas that also rely on informal water sources. This will help form a better idea of actual impacts of informal water sources on energy use and carbon emissions. More research is also needed to understand how the energy nexus of informal water systems contribute to socio-economic disparities.

References

Ahlers, R., Cleaver, F., Rusca, M., and Schwartz, K. (2014). Informal space in the urban waterscape: Disaggregation and co-production of water services. *Water Alternatives*. 7(1): 1-14.

Al-Saidi, M., & Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Science of The Total Environment*, *574*, 1131–1139.

Amit, R. K., & Sasidharan, S. (2019). Measuring affordability of access to clean water: A coping cost approach. *Resources, Conservation and Recycling*, *141*, 410–417.

Balazs, C. L., & Lubell, M. (2014). Social learning in an environmental justice context: a case study of integrated regional water management. *Water Policy*, *16*(S2), 97-120.

Balazs, C. L., & Ray, I. (2014). The drinking water disparities framework: on the origins and persistence of inequities in exposure. *American Journal of Public Health*, 104(4), 603-611.

Baquero, O. F., Gallego-Ayala, J., Giné-Garriga, R., de Palencia, A. J.-Fernández., & Pérez-Foguet, A. (2017). The Influence of the Human Rights to Water and Sanitation Normative Content in Measuring the Level of Service. *Social Indicators Research*, *133*(2), 763–786.

Bichai, F., Ryan, H., Fitzgerald, C., Williams, K., Abdelmoteleb, A., Brotchie, R., & Komatsu, R. (2015). Understanding the role of alternative water supply in an urban water security strategy: an analytical framework for decision-making. *Urban Water Journal*, *12*(3), 175-189.

Boateng, G. O., Collins, S. M., Mbullo, P., Wekesa, P., Onono, M., Neilands, T. B., & Young, S. L. (2018). A novel household water insecurity scale: Procedures and psychometric analysis among postpartum women in western Kenya. *PLOS ONE*, *13*(6), e0198591.

Brown, R. R., Keath, N., & Wong, T. H. (2009). Urban water management in cities: historical, current and future regimes. *Water science and technology*, *59*(5), 847-855.

Bulos, N & Yam, M. (2021, April 2). Climate change and corruption endanger an ancient valley in Lebanon. *LA Times*. https://www.latimes.com/world-nation/story/2021-02-21/bisri-valley-water

Christian-Smith, J., Balazs, C., Heberger, M., & Longley, K. (2013). Assessing water affordability. *A pilot study in two regions of California, Pacific Institute.*

Constantine, K., Massoud, M., Alameddine, I., & El-Fadel, M. (2017). The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of Environmental Management*, *188*, 85-94.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., ... & Yang, Q. (2018). Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*, *210*, 393-408.

Daou, R & Michael, M (2016). *The Bottled Water Market in Lebanon: Refreshingly Successful.* Blominvest Bank, Beirut, Lebanon.

Delgado, O., Rodríguez, F., & Muncrief, R. (2017). *Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020–2030 timeframe*. 76.

deMonsabert, S., & Liner, B. L. (1998). Integrated energy and water conservation modeling. *Journal of energy engineering*, *124*(1), 1-19.

El-Fadel, M., Maroun, R., Semerjian, L., & Harajli, H. (2003). A health-based socio-economic assessment of drinking water quality: The case of Lebanon. *Management of Environmental Quality: An International Journal*, *14*(3), 353–368.

Etikan, I. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1.

Fang, A. J., Newell, J. P., & Cousins, J. J. (2015). The energy and emissions footprint of water supply for Southern California. *Environmental Research Letters*, *10*(11), 114002.

Farrelly, M. A., & Brown, R. R. (2014). Making the implicit, explicit: time for renegotiating the urban water supply hydrosocial contract?. *Urban water journal*, *11*(5), 392-404.

Garfí, M., Cadena, E., Sanchez-Ramos, D., & Ferrer, I. (2016). Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *Journal of Cleaner Production*, *137*, 997–1003.

Gleick, P. H., & Cooley, H. S. (2009). Energy implications of bottled water. *Environmental Research Letters*, *4*(1), 014009.

Guinée, J. B., & Heijungs, R. (2000). Life cycle assessment. *Kirk‐Othmer Encyclopedia of Chemical Technology*.

Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. *Renewable and Sustainable Energy Reviews*, *65*, 319–331.

Hansen, L. G. (1996). Water and energy price impacts on residential water demand in Copenhagen. *Land Economics*, 66-79.

Hutton, G. (2012). *Monitoring "Affordability" of water and sanitation services after 2015: Review of global indicator options*. 95.

IEA (2019). *CO_2 Emissions from Fuel Combustion, 2019 edition*. International Energy Agency.

IPCC (2006). *Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories.* Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

Jaafar, H., Ahmad, F., Holtmeier, L., & King-Okumu, C. (2020). Refugees, water balance, and water stress: Lessons learned from Lebanon. *Ambio*, *49*(6), 1179-1193.

Jepson, W., & Vandewalle, E. (2016). Household water insecurity in the global north: a study of rural and periurban settlements on the Texas–Mexico Border. *The Professional Geographer*, *68*(1), 66-81.

King, C. W., & Carbajales-Dale, M. (2016). Food–energy–water metrics across scales: project to system level. *Journal of Environmental Studies and Sciences*, *6*(1), 39-49.

Kjellén, M., & McGranahan, G. (2006). *Informal water vendors and the urban poor* (pp. 978-1). London: International Institute for Environment and Development.

Komarulzaman, A. (2017). *Water affordability, water quality and their consequences for health and education in Indonesia* (Doctoral dissertation, Radboud Repository of the Radboud University, Nijmegen, the Netherlands).

Kooy, M. (2014). Developing informality: The production of Jakarta's urban waterscape. *Water Alternatives*, 7(1).

Kudva, N. (2009). The Everyday and the Episodic: The Spatial and Political Impacts of Urban Informality. *Environment and Planning A: Economy and Space*, *41*(7), 1614–1628.

Kyessi, A. G. (2005). Community-based urban water management in fringe neighbourhoods: the case of Dar es Salaam, Tanzania. *Habitat International*, *29*(1), 1-25.

Lebanese Center for Energy Conservation (LCEC). (2019). *The Evolution of the Solar Water Heaters Market in Lebanon*. Ministry of Energy and Water.

Lee, M., Keller, A. A., Chiang, P.-C., Den, W., Wang, H., Hou, C.-H., Wu, J., Wang, X., & Yan, J. (2017). Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. *Applied Energy*, *205*, 589–601.

Liddle, E. S., Mager, S. M., and Nel, E. L. (2016). The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *The Geographical Journal*, 182(1), 85–96.

Mahgoub, M. E. S. M., van der Steen, N. P., Abu-Zeid, K., & Vairavamoorthy, K. (2010). Towards sustainability in urban water: a life cycle analysis of the urban water system of Alexandria City, Egypt. *Journal of Cleaner Production*, *18*(10-11), 1100-1106.

Margane, A., Houben, G. (2010) *Water Supply within Beirut- Mount Lebanon*. Federal Institute for Geosciences & Natural Resources. Accessed on September 2020, https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Libanon/factsheet_water_supply.pdf?__blob=publicationFile&v=2

Ministry of Energy and Water (MoEW). (2010). National Water Sector Strategy. Retrieved from: http://www. databank.com.lb/docs/National%20Water%20 Sector%20Strategy%202010-2020.pdf

Misra, K. (2014). From formal/informal to emergent formalization: Fluidities in the production of urban waterworlds. Water Alternatives, 7(1)

MoE/UNDP/GEF (2019). *Lebanon's Third Biennial Update Report (BUR) to the UNFCCC*. Beirut, Lebanon.

Moore, E., Matalon, E., Pacific Institute (Oakland, Calif.), Community Water Center, Clean Water Fund (Washington, D. C.), & California Rural Legal Assistance Foundation. (2011). *The human costs of nitrate-contaminated drinking water in the San Joaquin Valley*. Pacific Institute. http://www.pacinst.org/reports/nitrate_contamination/nitrate_contamination.pdf

Nastiti, A., Sudradjat, A., Geerling, G. W., Smits, A. J. M., Roosmini, D., & Muntalif, B. S. (2017). The effect of physical accessibility and service level of water supply on economic accessibility: A case study of Bandung City, Indonesia. *Water International*, *42*(7), 831–851.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., & Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, *44*, 358–366.

Pattanayak, S. K., Yang, J. C., Whittington, D., & Bal Kumar, K. C. (2005). Coping with unreliable public water supplies: averting expenditures by households in Kathmandu, Nepal. *Water Resources Research*, *41*(2).

Peloso, M., & Morinville, C. (2014). 'Chasing for Water': Everyday Practices of Water Access in Peri-Urban Ashaiman, Ghana. *Water Alternatives*, 7(1).

Plappally, A. K., & Lienhard V, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, *16*(7), 4818–4848.

Ranganathan, M. (2014). 'Mafias' in the waterscape: Urban informality and everyday public authority in Bangalore. *Water Alternatives*, 7(1).

Rodríguez, F., Delgado, O., & Muncrief., R (2018). *Fuel consumption testing of tractortrailers in the European Union and the United States.* The International Council on Clean Transportation

Rogers, P., and Hall, W. (2003). Effective Water governance. In *GWP Technical Committee Background Papers No. 7*. Global Water Partnership, Stockholm.

Rosenberg, D. E., Tarawneh, T., Abdel-Khaleq, R., & Lund, J. R. (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research*, 43(7).

Roy, A. (2009). Why India cannot plan its cities: informality, insurgence and the idiom of urbanization. *Planning Theory*, 8(1), 76-87.

Russell, R. (2014). Waste not, want not? Evaluating the urban sustainability implications of centralized versus decentralized wastewater treatment in Tijuana, Mexico. *Urban geography*, *35*(6), 805-821.

Shaban, A. (2020). *Water resources of Lebanon*. Springer International Publishing.

Schuck, E. C., & Green, G. P. (2002). Supply-based water pricing in a conjunctive use system: Implications for resource and energy use. *Resource and Energy Economics*, *24*(3), 175-192.

Scott, C. A., et al., (2011). Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, *39*(10), 6622–6630.

Spang, E. S., & Loge, F. J. (2015). A High-Resolution Approach to Mapping Energy Flows through Water Infrastructure Systems: Mapping Energy Flows through Water Infrastructure. *Journal of Industrial Ecology*, *19*(4), 656–665.

Spang, E. S., Manzor, S., & Loge, F. J. (2020). The cost-effectiveness of energy savings through water conservation: a utility-scale assessment. *Environmental Research Letters*, *15*(11), 114031.

Stokes, J., & Horvath, A. (2006). Life Cycle Energy Assessment of Alternative Water Supply Systems (9 pp). *The International Journal of Life Cycle Assessment*, *11*(5), 335–343.

Stokes, J. R., & Horvath, A. (2009). Energy and Air Emissions Effects of Water Supply. *Environmental Science & Technology*, *43*(8), 2680–2687.

Schwartz, K., Tutusaus Luque, M., Rusca, M., & Ahlers, R. (2015). (In) formality: the meshwork of water service provisioning. *Wiley Interdisciplinary Reviews: Water*, *2*(1), 31-36.

Teodoro, M. P. (2018). Measuring Household Affordability for Water and Sewer Utilities: Measuring Household Affordability for Water and Sewer Utilities. *Journal - American Water Works Association*, *110*(1), 13–24.

United States Environmental Protection Agency (US EPA) (2006). *Life-cycle assessment: principles and practice.* National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268

Walter, C. T., Kooy, M., & Prabaharyaka, I. (2017). The role of bottled drinking water in achieving SDG 6.1: An analysis of affordability and equity from Jakarta, Indonesia. *Journal of Water, Sanitation and Hygiene for Development*, 7(4), 642-650.

Workman, C. L., & Ureksoy, H. (2017). Water insecurity in a syndemic context: Understanding the psycho-emotional stress of water insecurity in Lesotho, Africa. *Social Science & Medicine*, *179*, 52–60.

Wutich, A., Beresford, M., & Carvajal, C. (2016). Can Informal Water Vendors Deliver on the Promise of a Human Right to Water? Results from Cochabamba, Bolivia. *World Development*, *79*, 14–24.

Young, S. L., Collins, S. M., Boateng, G. O., Neilands, T. B., Jamaluddine, Z., Miller, J. D., ... & Schuster, R. C. (2019). Development and validation protocol for an instrument to measure household water insecurity across cultures and ecologies: the Household Water InSecurity Experiences (HWISE) Scale. *BMJ open*, 9(1), bmjopen-2018.

Zawahri, N., Sowers, J., & Weinthal, E. (2011). The Politics of Assessment: Water and Sanitation MDGs in the Middle East: Water and Sanitation MDGs in the Middle East. *Development and Change*, *42*(5), 1153–1178.

Appendix I: Values and Assumptions per Source and Stage

Formal Piped Infrastructure

Formal piped infrastructure has three delivery stages: pumping groundwater, water treatment and distribution through pumping stations (Refer to **Table 16**). Assumption and values of delivery stages are developed further below.

Pumping Groundwater

Calculations are based on the nameplate pumping capacity and operation hours of southern and northern wells with their weighted average. Northern wells supply 77% of total volume compared to 23% for Southern wells (Beirut and Mount Lebanon Water Establishment):

- Nameplate hydraulic power: 68 kW.
- Nameplate pumping capacity: 3,220 m^3/Day.
- Operating hours: 6.5h/Day.
- Daily electrical consumption: 442 kWh/Day

➢ EV (kWh/m^3) = 442 (kWh) / 3,220 (m^3)

➢ CEV (kg of CO_2/m^3) = 442 (kWh) / 3,220 (m^3) x 0.774 (kg of CO_2/ kWh)

Water treatment

Dbayeh water treatment plant has four treatment steps of screening, flocculation, filtration (rapid sand filtration), and chlorination (Margane & Houben, 2010) with the following energy intensity:

Table 22 - Energy Intensity of Water Treatment Steps (Based on Plappally & Lienhard, 2012)

Treatment Steps	Energy Use kWh/m^3
Sedimentation	0.0008
Coagulation	0.5500
Gravity Filtration	0.0095
Surface water chlorination/de-chlorination	0.0003
Total	**0.5605**

With a total treated volume of 200,000m^3 per day (Beirut and Mount Lebanon Water Establishment) we calculated the electrical consumption as: Energy Use per cubic meter (kWh/m^3) x Total Treated Volume (m^3) = 112,102 kWh.

- EV (kWh/m3) = 0.56 (kWh/m^3), (Plappally & Lienhard, 2012).
- EC (kg of CO_2/m^3) = 112,102 (kWh) / 200,000 (m^3) x 0.774 (kg of CO_2/ kWh)

Distribution

Calculations based on the nameplate pumping capacity and real values of operating hours of four pumping stations with their weighted averages (Beirut and Mount Lebanon Water Establishment):

  - Nameplate hydraulic power: 505 kW
  - Nameplate pumping capacity: 81,190 m3/Day.
  - Operating hours: 22h/Day.
  - Daily electrical consumption: 11,275 kWh/Day

- EV (kWh/m^3) = 11,275 (kWh) / 81,190 (m^3)
- CEV (kg of CO_2/m^3) = 11,275 (kWh) / 81,190 (m^3) x 0.774 (kg of CO_2/ kWh)
-

Tanker Trucks

Tanker trucks have two delivery stages: pumping groundwater, distribution through water trucks (Refer to **Table 16**). Assumption and values of stages are developed further below.

Pumping Groundwater

Pumping groundwater is based on the following:

  - Average hydraulic power: 67 kW (Beirut and Mount Lebanon Water Establishment). The groundwater pump sizes for the tanker trucks were not available. Thus, we assumed that tanker trucks use the same pump sizes for groundwater pumping as the formal piped infrastructure. This assumption was later confirmed as reasonable by a water establishment engineer (El Asmar, personal communication, July 1st, 2020).

    - Pumping capacity: 183 m^3/Day, based on the tanker trucks survey.
    - Average operating hours: 6 h/Day, based on the tanker trucks survey.
    - Average electrical consumption: 396 kWh.
- ➢ EV (kWh/m^3) = 396 (kWh) / 183 (m^3)
- ➢ CEV (kg of CO2/m^3) = 396 (kWh) / 183 (m^3) x 0.774 (kg of CO_2/ kWh)

Distribution

Transportation of water is based on the following:

- Fuel economy: 33.1 L of fuel/ 100 km. The tanker interviews show that the average size of trucks is around 20 tons. We assumed that tanker trucks are equivalent to Long Haul Trucks with an average payload weight of 19.3 tons (almost equal to 20 tons) with fuel economy baseline of 33.1 L of fuel /100km including a 41.9% engine brake thermal efficiency, (Rodríguez et al., 2018; Delgado et al, 2017).
- Emissions Factor: 2.7 kg CO_2 /L of diesel.
- Energy content of Gasoline: 38.6 MJ per L of fuel.
- Travelled Distance: 40 km. Based on the residential interviews we assume that, for 1 delivery order, tanker trucks travel a distance of 40 kilometers (equivalent to a roundtrip from the location of the wells in Beirut's suburbs to case study area including traffic). We omitted any stop per delivery trip and consider that trucks transport water from the wells directly to the case study area.
- Truck Volume: 19 m^3. Since 1 ton of water is equal to 1 m^3, we considered that the volume of water transported is equivalent to the trucks' payload weight with 19m^3 for the tanker trucks.
- ➢ ET (kWh/m^3) = 33.1 (L of fuel/ 100 km) x 34.8 (MJ/L of fuel) x 40 (km) / 19 (m^3)/100
- ➢ CET (kg of CO_2/m^3) = 33.1 (L of fuel/ 100 km) x 2.7 (kg CO_2/L of diesel) x 40 (km)/ 19(m^3)/100

Bottles

Bottles have three delivery stages: pumping groundwater, treatment through cleaning, filling, sealing and labeling bottles, and distribution through regional delivery trucks (Refer to **Table 16**). Assumption and values of stages are developed further below.

Pumping groundwater

Pumping groundwater is based on the following:

- Average hydraulic power: 67 kW, same as the water tanker pump size data (Beirut and Mount Lebanon Water Establishment).
- Average operating hours of pumps: 24 h/Day, (El Asmar, personal communication, January 05, 20201.
- Pumping capacity: 2,055 m^3/Day (Daou & Mikhael, 2016).
- Average electrical consumption: 1,604 kWh

➢ EV (kWh/m^3) = 1,604 (kWh) / 2,055 (m^3)

➢ CEV (kg of $CO2/m^3$) = 1,604 (kWh) / 2,055 (m^3) x 0.774 (kg of CO_2/ kWh)

Water treatment

Gleick and Cooley (2009) is one of the only studies in water-energy nexus literature that focuses on bottled water and looks at the energy footprint for various phases of water production, transportation, and use. Spring water is sometimes treated through processes such as ultrafiltration, ozonation, ultraviolet radiation, and reverse osmosis. This study used typical treatment techniques applied in bottling plants using their average energy requirements:

Table 23 - Energy requirements for treatment of spring water (kWh/m^3) (Based on Gleick and Cooley, 2009)

Treatment Techniques	**Level of Treatment**	**Energy Use (kWh/m^3)**
Ozone	Pre-Oxidation	0.03
	Disinfection	0.1
Ultraviolet (UV) radiation	Bacteria	0.01

(Medium pressure)	Viruses	0.03
Microfiltration/Ultrafiltration		0.085
Reverse Osmosis	Source TDS=500ppm	0.66
Total		**0.915**

- EV (kWh/m^3) = 0.92 (kWh/m^3), (Gleick and Cooley, 2009)
- CV (kg of CO_2/m^3) = 0.92 (kWh/m^3) x 0.774 (kg of CO_2/ kWh)

Distribution

Transportation of water is based on the following:

- Fuel economy: 36.4 L of fuel/ 100 km. We assumed that regular delivery trucks are equivalent to Regional Delivery Trucks with an average payload weight of 12.9 tons with a baseline fuel economy of 37.4 liters of fuel/100km including a 44.8% engine brake thermal efficiency, (Rodríguez et al., 2018; Delgado et al, 2017).
- Emissions Factor: 2.7 kg CO_2 /L of diesel.
- Energy content of Gasoline: 38.6 MJ per L of fuel.
- Travelled Distance: 200 km. Based on the residential interviews we assume that, for 1 delivery order, delivery trucks travel a distance of 200 kilometers (equivalent to the average roundtrip distance from two major springs in Mount Lebanon – Sohat and Sannine – to the case study area including traffic). We also omitted any stop per delivery trip and consider that trucks transport water from the sources directly to the case study area.
- Truck Volume: 12 m^3. Since 1 ton of water is equal to 1 m^3, we considered that the volume of water transported is equivalent to the trucks' payload weight with 12 m^3. We excluded the weight of plastics.

- ET (kWh/m3) = 36.4 (L of fuel/ 100 km) x 34.8 (MJ/L of fuel) x 200 (km)/ 12 (m^3)/100
- CET (kg of CO2/m^3) = 36.4 (L of fuel/ 100 km) x 2.7 (kg CO_2/L of diesel) x 200 (km)/ 12(m^3)/100

Private Domestic Wells

Private domestic wells have two delivery stages: pumping groundwater, water treatment through reverse osmosis. Assumption and values of stages are developed further below.

Pumping Groundwater

Groundwater pumping calculations are based on the following:

- Average Hydraulic Power: 1HP (0.745 kW), typical domestic pump size, (El Asmar, personal communication, February 14, 2020).
- Average Hours of Operation: 47 minutes/building/day (based on the household survey. Which is equal to 0.014 h/Day.
- Average electrical consumption of household pumps: 0.011 kWh/Day.

➢ EV (kWh/m3) = 0.011 (kWh)/ 0.018 (m^3)

➢ CEV (kg of CO2/m^3) = 0.011 (kWh) / 0.018 (m^3) x 0.774 (kg of CO_2/ kWh)

RO Treatment

RO treatment values are based on Garfí et al (2016). They look at the environmental impacts caused by drinking water consumption in Barcelona using a Life Cycle Assessment methodology. They develop multiple scenarios one of which takes into consideration domestic reverse osmosis units installed on tap water (that is usually delivered from conventional drinking water treatment plants). The study looked at the energy requirements of various domestic reverse osmosis units based on two local manufacturers. Assuming that most of the Lebanese products are usually important from European markets (MoE/UNDP/GEF, 2019), we used the average of the values provided by Garfí et al (2016) of 0.5 (kWh/m^3).

➢ EV (kWh/m^3) = 0.5 (kWh/m^3), (Garfí et al, 2016)

➢ CEV (kg of CO_2/m^3) = 0.5 (kWh/m^3) x 0.774 (kg of CO_2/ kWh)

Internal Building Pumping

Internal building pumping has one delivery stage: distribution through internal pumping at building level from lower to upper reservoirs. Assumption and values are developed further below.

Distribution

Pumping water internally is based on:

- Average Hydraulic Power: 1HP (0.745 kW), typical domestic pump size, (El Asmar, personal communication, February 14, 2020).
- Average Hours of Operation: 0.078 h/Day, based on the household survey.
- Average pumped volume: 0.652m^3/Day, based on the household survey.
- Average electrical consumption of household pumps: 0.058 kWh/Day.

- ➢ EV (kWh/m3) = 0.058 (kWh)/ 0.652 (m^3)
- ➢ CEV (kg of CO2/m^3) = 0.058 (kWh) x 0.774 (kg of CO_2/ kWh) / 0.652 (m^3)

Chapter 4: Cooperation and Competition in an Informal Network: Water Tankers in Beirut, Lebanon

Abstract

Many communities that experience chronic water shortages rely on water deliveries from informal water tanker trucks for their water use. As non-state stakeholders, informal water tankers usually rely on their social relations to manage water sources. Their relations can sometimes be amicable, and collaborative and other times conflictual and competitive. The organization, interactions and relations of these informal stakeholders has been rarely studied because of their informal and hidden characteristics. We use a Social Network Analysis (SNA) approach to identify the network of informal water tankers in Beirut (Lebanon), study their relationships and understand drivers that lead them to cooperate and compete. Cooperation and competition usually happens around clients, maintenance of trucks, wells, and/or prices. We compare the networks' descriptive analysis at macro, meso and micro levels and present the networks' Exponential Random Graph Models (ERGMs). Our analysis is supplemented and supported by qualitative data from our interviews. Our results show that cooperation and competition are mainly influenced by stakeholder religion and years' operating in the market. Cooperation mainly occurs among Christian tanker firms that have been in the market longer. Information exchange across these cooperative networks tends to focus on nonessential information such as service quality and truck maintenance. In contrast, competitive stakeholders tend to be more religiously diverse and have entered the market more recently. Through their external connections they acquire new and restricted information such as market price and new service areas. The competitors' new market entry coincides with recent droughts in Lebanon, which have increased household water intermittence and insecurity and expanded use of informal water tankers, suggesting a local effect of climate change. Competition is double sided. It reduces market prices, making water more accessible to end-users. However, competition also can lead to a tragedy of the commons from excessive groundwater pumping.

NB: Throughout this document, the names of the informal water tankers are coded, abiding by IRB confidentiality and privacy principles.

Introduction and Literature Review

Water extraction and use is complex because, as with any common pool resource, water involves many social-ecological interdependencies (McGinnis and Ostrom, 2014*)*, where hydrologic and social layers interact (Swyngedouw 2006). Water is driven by public and private stakeholders from different sectors and multiple administrative levels, representing different political interests and expertise (Ingold et al 2018; Mancilla Garcia et al 2019) that employ their various political, economic and cultural relations (Swyngedouw, 2004). These public and private stakeholders typically represent (formal) regulated and legalized governmental and non-governmental organizations and institutions, (detailed in **Appendix II, Table 36).**

In much of the world, complexity is greater when non-state and informal stakeholders control and manage water sources and affect access to water (Adam and Kreisi, 2007). Around 30% to 60% of people with chronic water shortages rely on informal water suppliers for some or all of their daily water uses (Ahlers et al. 2014). These informal suppliers tend to operate in greater autonomy (Stein et al., 2011) with “little or no state regulations” (London et al, 2021). In some areas, they are accepted as new modes of water provision (Ahlers et al. 2014; Wutich et al 2016; Walter et al 2017). So they are seen as a nuanced mode of governance that operate at multiple scales, are powered by their own interests, and enable water access to those with water shortages (Cheng, 2014; Swyngedouw, 2005; Ahlers et al. 2014; Peloso and Morinville, 2014).

The organization and interaction of these informal water suppliers has been rarely studied (but see Wutich et al 2016). Unlike formal institutions, understanding their social relations and impact on water sources is challenging because of the nature of their informality, i.e. hidden characteristics and lack of regulation (Bakker et al 2008). Usually, it is not easy to identify these suppliers, their total number, activities, and relationships. Identifying and characterizing these informal water suppliers becomes essential to understand their roles in the overall water system.

Informal water suppliers rely on their social relations to interact with other suppliers and end-users to manage water sources (Ahlers et al. 2014; Jepson and Vandewalle, 2016; Balazs and Lubell, 2014). Their relations can sometimes be amicable and collaborative, and at other times conflictual and competitive (Cheng, 2014). Collaboration and competition can be based on the type of information shared among stakeholders, they happen for multiple reasons and can impact resources in different ways, including control of resource use and extraction (Easter et al., 1999), service quality, and service price (Solo, 1999). Collaboration can help informal water suppliers self-regulate water prices and control the quality of delivered water (Wuitch et al., 2016). Competition also can lead to the control of water access (e.g. using wells) and of market prices (Easter et al., 1999; Collignon & Vézina, 2000). Analyzing the dynamics of informal suppliers' relationships and aspects of collaboration and competition helps us understand their impact on the overall water system and water users.

We use a Social Network Analysis (SNA) approach to identify the network of informal water tankers in Beirut (Lebanon) and study their relationships. Networks usually are formed across nodes (also called actors) connected through social ties. In our case study, the nodes are the informal water tanker businesses connected through cooperative or competitive ties. Cooperation and competition results in informal tankers altering their behavior or type of information that is being shared between them (Barnes et al., 2017). They can either work amicably together, communicating or helping each other over clients, maintenance of trucks, wells, and/or prices. Or they can conflict or fight over these issues. This study has two main objectives: 1) identify the most influential individuals in the informal water tanker network (which we will refer to as key individuals) and identify main characteristics that drive their cooperation and/or competition, 2) understand their relationship by analyzing their types of ties and type of information that is being shared. Based on these objectives, we develop our hypotheses:

Hypothesis 1a: Key individuals drive both cooperation and competition among informal water tankers. Key individuals are the most influential individuals in a network because they tend to have direct ties (social relations) with more stakeholders (Alexander et al 2018). They can drive both cooperation and competition in the network. They can help form new ties, facilitate the distribution of information, and improve overall coordination (Berardo, 2014; Robbins and Lubell, 2020). However, in competitive situations, they can limit cooperation by choosing not to cooperate (Bodin and Crona 2009). In this study, we identify and characterize key individuals in both the cooperative and competitive networks using quantitative network analysis.

Hypothesis 1b: Cooperation increases among informal water suppliers sharing similar characteristics, while competition is greater among those with different characteristics.

Informal water suppliers tend to form ties with those that share similar attributes or beliefs, referred to as homophily (Henry et al 2011). However, patterns of homophily can also lead to conflict (Poteete and Ostrom 2004; Baerveldt et al. 2004), especially when stakeholders emphasize their own ethnicity within their group and their differences from other groups (Barnes-Mauthe et al., 2013). In many cases, this can create an “us and them” attitude (Borgatti and Foster, 2003), where suppliers of similar ethnic identity cooperate more, while those of different ethnicities compete. For our case study, we are interested in finding main characteristics that improve social relations and increase the formation of social ties that impact cooperation and competition.

Hypothesis 2: Different types of ties improve cooperation and can lead to competition.

Networks tend to be composed of multiple subgroups and differ in their connections. They can have within subgroup ties, where nodes connect internally (which are referred to as bonding ties), or they can have between subgroup ties, where nodes connect across subgroups (which are referred to as bridging ties). Within subgroup ties can increase internal trust and trigger internal collaboration (Berardo, 2014). However, their intensive bonding ties can lead to subgroup isolation, (Alexander et al 2018), which can reduce collaboration at the broader network level. Between subgroup ties help establish connections with distant actors (Berardo and Scholz, 2010), which has a positive effect on trust and beliefs, improving broader collaborative actions (Schneider et al 2003). In our case, we want to analyze which type of ties (bonding or bridging) increase cooperation and/or competition.

Table 24 - Hypotheses and Aspects of Collaboration and Competition.

Hypotheses	**Network Structure** (SNA Nomenclature)	**Aspects of collaboration**	**Aspects of competition**
Hypothesis 1a: Key Individuals	Node Centrality	• Individuals at central nodes can coordinate, share information and solve problems. • Central nodes tend to have higher number of ties.	• Information flows among few actors, which leads to the formation of network clusters.
Hypothesis 1b: Characteristics of Stakeholders	Homophily	• Higher cooperation among actors of similar characteristics.	• Only specific information is shared. • Unwillingness to share information with actors of different characteristics. • Increases network segregation and conflict.
Hypothesis 2: Type of Ties of Stakeholders and Subgroups	Bonding and Bridging Ties	• Within subgroups ties can increase economic productivity and increase levels of collaborations. • Across subgroups ties enable the exchange of new information and improve overall collaboration.	• Within subgroups ties reduce information exchange across the broader network. • High level of within subgroups ties can lead to fragmentation and impact policy outcomes.

Table 24 shows how each hypothesis is based on network structure and how those structures can lead to different aspects of collaboration and competition. This summary was derived from SNA review papers by: Bodin et al (2006); Janssen et al (2006); Bodin and Crona, (2008); Henry and Vollan, (2014); and Berardo et al, (2016). More details appear in **Appendix I- Table 35.**

Literature Review

The literature on informal water systems has so far focused on theoretical definitions and empirical analysis of socio-economic implications of informal sources on water insecurities and water disparities. Theoretically, studies have defined informality by analyzing its relation and interdependence with formal systems (Roy, 2005; Kudva, 2009; Ahlers et al., 2014; Schwartz et al., 2015; Liddle et al 2016). Empirically, studies have quantified socio-economic impacts of informality using estimated added cost of informal sources or results of water access disparities (Pattanayak et al., 2005; Moore et al., 2011; Christian-Smith et al., 2013; Nganyanyuka et al., 2014; Watler et al., 2017; Nastiti et al., 2017; Komarulzaman 2017; Amit and Sasidharan 2019). Also, they have analyzed psychological distresses of end-users from water insecurity (Jepson et al 2017 a, b; Young et al., 2019,) and investigated health hazard impacts from water quality and waterborne diseases from unmonitored informal water sources (El-Fadel et al., 2003; Kjellén & McGranahan, 2006; Constantine et al 2017). Few studies have looked at the stakeholders behind informal water systems (e.g. Wutich et al., 2016). Identifying and characterizing informal stakeholders is essential for understanding their role in the overall water system governance.

Social network analysis (SNA) looks at structures and patterns of connections among nodes and has been effective in characterizing social relations among stakeholders (Fischer and Ingold, 2020). SNA is mainly used to analyze aspects of collaboration (Bodin et al 2020; Mancilla Garcia et al., 2019) of formal public and private institutions (Berardo, 2009; Sandström and Rova, 2009; Angst and Fischer 2020) and self-organized networks (Bodin and Crona, 2008; Alexander et al., 2018; Barnes et al 2016; Barnes et al 2017) (refer to **Appendix II- Table 36**, and **Appendix III-Table 37**). Collaboration has been a focus in this field of environmental governance because of its positive impact on resource management. Collaborative approaches generally promote engagement among stakeholders (Ansell and Gash 2007; Emerson et al 2012) which helps develop collective actions to resolve environmental problems (Ansell and Gash 2007; Emerson et al 2012; de Lange et al, 2019; Pahl-Wostl, 2009; Balazs & Lubell; 2014) and achieve desired social and environmental outcomes (Eklund & Cabeza 2017). However, collaboration does not always lead to significant systemic behavioral and environmental change (Bodin, 2017), and can coincide with competitive behavior (Bodin et al 2020; Mancilla Garcia et al., 2019).

By combining SNA with a framework of informality, we can identify and characterize the activities of informal stakeholders and understand their role within overall water system governance. We use SNA to analyze simultaneous collaborative and competitive relations among informal water tankers. This provides an understanding of the socio-cultural drivers that affect how informal stakeholders manage and control water sources, and their impact on the overall water system and its users.

Case Study Details

Piped water supply for Beirut comes from two main areas, shown on **Map 6**. The main source is a northern water treatment plant in Dbayeh, which receives and treats water from two springs upstream and from 17 additional wells. The plant supplies around 77% of the city's water use. The second largest water source, supplying 23% of total city water use, is groundwater from a cluster of 11 wells in the southern Naameh area. Water from these locations is usually pumped to reservoirs in Beirut for storage before final residential delivery. The reservoirs cannot supply water on a 24/7 basis, so they pump water every 48 hours. And residents receive daily water for a continuous period of around 3 hours in the summer and around 7 hours in the winter. To cope with water intermittence, most households also purchase freshwater from informal water tankers. These tanker businesses tend to be unregistered and operate in complete independence and autonomy from the government (Personal communication Howayek, 2019). They are usually managed by private individuals that own one or several tankers, and we will refer to them as informal water tanker businesses.

Technical Characteristics: Business Models, Water Sources and Qualities

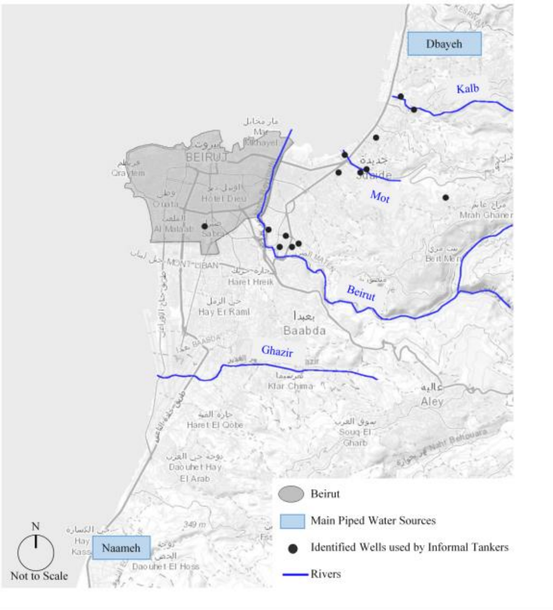
Businesses typically own 1 to 20 tanker trucks, that can carry from 1,000 to 30,000 liters. The businesses operate mainly in water intermittence periods, usually in summer and dry seasons. During peak periods, some businesses can have trucks delivering to multiple customers per day, reaching up to 70 truck trips per day. During winter, when overall water demand decreases and households have less frequent shortages from the piped infrastructure, demand for tanker supplies almost disappears. Some businesses have an owner with multiple drivers and for other businesses the owner is the driver. Trucks also vary in branding. Larger businesses tend to brand their trucks showing the company’s name, logo and phone number, whereas smaller businesses tend to operate with minimal brand identity, as shown in **Figure 13**.

Figure 13 - Typical tanker trucks for different sizes and branding identity.

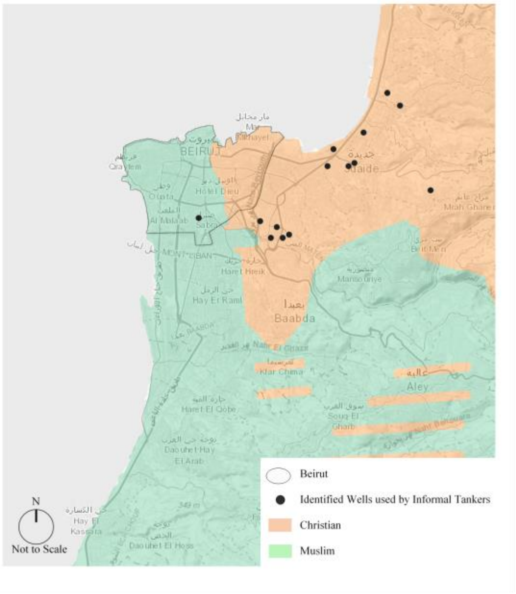
Both registered and unregistered wells supply water to these tanker businesses. Some businesses own their wells, others lease wells by the year, and a third group just pays a fee per liter of pumped water. The location of tanker businesses is usually determined by the location of these wells. **Map 6** shows some tanker businesses that this study could identify and locate. Being an informal network, the complete number and location of tanker businesses was unavailable through official or unofficial documents. In terms of water quality and availability, the north-eastern periphery of the city is water rich, because of the presence of rivers (the Kalb, Mot and Beirut rivers) that replenish groundwater and provide year-round water availability (Shaban, 2021). According to interviewed tankers, the quality of wells in this area is acceptable and they claim to regularly use water quality tests to check bacterial and salt levels (although no official or unofficial test results were provided for this study). Wells within Beirut, those with lower altitudes (and closer to the sea), and those on the southern periphery of the capital, are of lower quality because of seawater intrusion from years of over-extraction (Alameddine et al 2018). Nevertheless, some tanker businesses locate in those areas. They either provide lower quality salty water (Personal communication Tanker Owner SK, 2019), or apply UV and/or RO filtration systems to improve water quality (Personal communication Tanker Owner AS, 2019), as shown in **Figure 14**.

Figure 14 - Filtration system used by one of the tanker businesses.

Map 6 - Location of Informal Water Tankers Identified During Data Collection.



Map 7 - Ethnic diversity of Informal Water Tankers (Based on Izady, 2010).



Ethnic Diversity

The oldest informal tankers are based in the water-rich, northeastern periphery of the capital (**Map 6**), (Personal communication Tanker Owner CHR, 2019). In Lebanon, after 15 years of civil war, religion is an important demographic trait (Faour, 2007) and structures local tanker operations. In the northeastern region, the informal water market has historically been led by Christian owners, with a minor presence of Muslim owners (**Map 7**). However, the demographics of the tanker operations are changing. Several droughts in recent years (Gray, 2016; Sarant, 2021) have reduced piped water deliveries and increased demand for water from tankers, creating more opportunities for informal tanker businesses (Maloy, 2017). Newer informal tanker entries have been mainly Muslim owners (Personal communication Tanker Owner SK, 2019), so the ratio of Christian to Muslim informal water tankers has been decreasing in recent years.

Data Collection

Qualitative data identified tanker businesses (the nodes) and their characteristics, and quantitative data identified the number and type of ties (cooperative or competitive) between businesses.

Data was collected from in-person semi-structured interviews with truck owners and managers in and around Beirut over a two-month period, from August 2019 to September 2019. The target population was defined as any person that owns or manages at least one informal water tanker. Interviews were at offices of water tanker businesses (except for two conducted in cafés). The interviews were in Arabic and all answers were collected as written notes by the researcher. Interviewees were recruited with a convenience sampling process, based on their ease of accessibility, willingness to participate, and geographic location (Etikan, 2016). At the end of every interview, a new list of informal truck owners was generated. The researcher would then contact by phone the new list of names to take appointments. This sampling process was repeated until contact list closure was reached, and the direct contact list was exhausted, i.e. no new truck contact was answering for new appointments (Alexander et al 2018; Hanneman and Riddle 2005). An estimate of the total number of trucks operating in the region was not available; thus it was not possible to gauge the size of the overall network. In total, we interviewed 20 truck owners and managers from a total list of 68 identified informal water tanker businesses, for an overall response rate of 29%.

Qualitative Data

Semi-structured interviews elicited information on the characteristics of informal water truck owners, and factors that have affected and potentially changed their businesses. This qualitative data was particularly helpful in contextualizing the study (Bodin et al. 2019) and helped reveal more detailed characteristics of tanker businesses. Interviewees were asked to describe their business, in particular focus on their perception of how the business has changed (since their first year of operation compared with 5-10 years ago, and today), and their opinion on what has contributed to this change. They were also asked to describe their relationship with the government, and the formal water establishment. Basic attribute data were also collected for each interviewee including: business size (i.e. number of clients, and number of trucks), geographic focus (i.e. business location, service location and well location), and water quality (i.e., number of wells used and their water quality). Religious background was inferred from the names of the owners and not directly asked, given the sensitivity of this topic in the region.

Quantitative Data

Quantitative network data focused on number and type of ties among truck businesses (collaborative or competitive), and factors that contribute to tie formation. Collection of network data used a free recall method (Marsden 2011). Sampling started with one main business owner. There was no limit on the number of nominated individuals (Alexander et al 2018), as it was important to collect as many names as possible, since network size was unknown. This approach tends to capture strong ties (based on the number of ties) (Chua et al, 2011; Alexander et al 2018) which helped identifying key individuals (Alexander et al., 2018). Interviewees were asked to list individuals and briefly describe their relation (cooperative or competitive), reasons for both and type of information exchange (Crona and Bodin, 2006). A cooperative relationship was defined as having mainly worked amicability together, communicating or helping each other over clients, maintenance of trucks, wells, and/or prices. Competition was defined as having had an argument, conflict or fight over multiple issues including clients, prices, and/or wells. Cooperation and competition might sometimes happen simultaneously with the same tanker business, or other times, relationships might switch from cooperation to competition and vice versa. However, we asked the interviewee to choose the more dominant type of interaction during the time of the interview, without considering the evolution of relationships.

Analysis

The analysis is divided in three parts. After finding tankers that cooperate and compete, we start by dividing the overall network of informal water tankers in two networks: one composed of cooperative ties, and another composed of competitive ties. Cooperation is defined as working amicability together, communicating or helping each other over clients, maintenance of trucks, wells, and/or prices. Competition is defined as having had an argument, conflict or fight over the same issues. Cooperation and competition can happen simultaneously or might change over time. However, we only recorded the dominant type of interaction during the interview process. Hence the analysis only includes this dominant type without taking into consideration any temporal dimension of the evolutions of relationships. For each network, we compare their descriptive analyses combined with qualitative data, and finally, present the networks' Exponential Random Graph Models (ERGMs). The descriptive analysis qualitatively compares and analyzes networks at macro, meso, and micro levels. The ERGMs statistically compare and account for network configuration and node attributes.

Creating Cooperative and Competitive Networks

From the interviews, we use three elements to develop the networks: 1) list of names of stakeholders connected to each other, 2) their characteristics, and 3) type of connections (cooperative or competitive).

We first develop a data frame (called an edge list in SNA) with all stakeholder names, their characteristics and connections. Then, depending on whether the connection is cooperative or competitive, we separate this data frame in two (cooperative and competitive edge lists). We build each network by combining the edge list and node list, allowing us to specify two cooperative and competitive networks composed of their respective edges and nodes, and the connections are directed showing the source of the connection and targeted connection.

Descriptive Social Network Analysis

The descriptive analysis of cooperative and competitive networks is analyzed at macro, meso and micro levels, using the igraph package generated in R (Team R, 2013; Csardi and Nepusz, 2006). This three-tier approach helps develop a holistic understanding of the networks (Bodin et al 2020; Wassermann and Faust 1994; Borgatti et al. 2018, Fischer and Ingold 2020, Ebrahimiazarkharan et al 2020). The macro-level analysis identifies overall networks characteristics; the meso-level analysis detects clustering and subgroups; and, the micro-level analysis identifies key individuals. **Table 25** summarizes components used in each analysis level, with a brief description and hypotheses. More component details and calculation methods are described in **Appendix IV**.

Table 25 - Descriptive Analysis: Three levels and Components

Analysis Levels	Components
Macro-Level: Overall Network Characteristics	**Density:** The proportion of observed ties compared to all theoretically possible ties. This identifies the cohesiveness of the network. **Size:** Total number of nodes (stakeholders) and edges (ties). **Diameter:** The longest shortest path in a network. This identifies whether stakeholders are well connected and integrated. Distance is measured by the number of ties. **Mean Distance:** The average length of the shortest path between two stakeholders. This identifies whether stakeholders are well connected and integrated. **Assortativity (H2):** Quantifies the extent to which connections are influenced by stakeholders sharing similar attributes. In our case we take religion as an attribute and calculate whether it plays a role in tie formation.

	Reciprocity (H1b): Identifies the proportion of ties that are reciprocated among two stakeholders. This is indicative of bonding ties.
Meso-Level: Network Clustering	**Subgroup Detection and Modularity (H1b):** Identifies the number of subgroups in a network and the proportion of within subgroup ties versus across subgroup ties, which helps detects bonding and bridging ties. **Coreness (H1a):** Identifies stakeholders with the highest number of ties that are at the core of the network. This helps detect the most influential subgroup. **Largest Clique (H1a):** Identifies largest subgroup of nodes that are all directly connected to one another. This helps detect the most influential subgroup.
Micro-Level: Nodal Characteristics	**Degree Centrality (H1a):** Identifies stakeholders with the highest number of direct connections. This helps detect the most connected stakeholders. **Betweenness Centrality (H1a):** Identifies stakeholders that are in-between groups. Their position in the network is important as they connect different subgroups that would otherwise be disconnected. **Closeness Centrality (H1a):** Indicates how close a stakeholder is to all other stakeholders in the network, hence their level to connect and spread information. **Eigenvector Centrality (H1a):** Indicates whether stakeholders are connected to important stakeholders (for example those with high number of ties). If they have a high number of important connections, than they will also be important in the network.

H1a= Hypothesis 1: Key Individuals.
H1b= Hypothesis 3: Similar Characteristics (Homophily).
H2= Hypothesis 2: Type of ties (Bonding and Bridging ties).

To better understand factors that enable collaboration and competition, the results produced at each analysis level are cross-referenced with qualitative data, using stakeholder's characteristics (attributes) (Robbins and Lubell, 2020). The main attributes that we focused on included religion (Christian or Muslim), years of operation, and size of businesses (measured by number of tankers). We are aware that generally there are sub-religious Christian and Muslim sects (e.g. Catholics, Orthodox, Sunni, Chia etc…), and Lebanon has around 17 recognized sub-religious sects (Prados, 2006). For simplicity, this study does not go into these sub-religious groups, and analyzes religion as two general types as Christian and Muslim. Moreover, as mentioned in the data collection section, given the sensitivity of this topic in the region, religion type was inferred from the names of the owners based on these two general types.

For the micro-level analysis, we followed a ranking method to identify key individuals (modified from Bodin and Crona 2008). For each centrality level (**Table 25:** Degree, Betweenness, Closeness and

Eigenvector), the top 5 nodes are given a score of 10, and all nodes below are given a score of 0. The total scores for all criterion are then computed and tanker businesses with the highest total score are identified as key individuals. The total number of key individuals is limited to 5, representing 10% to15% of the sample population for both networks

Exponential Random Graph Modeling

Exponential Random Graph Models (ERGMs) are statistical models that explain patterns of ties in a social network leading to network structure (Lusher et al, 2014). They model the configuration probability of an observed network, compared to all other network configurations that have the same number of nodes and density (Lusher et al, 2014). Patterns enable inference of the processes and drivers that lead to tie formation by statistically analyzing network configuration and node attributes (Lusher et al, 2014). In our case we focus on tie formation within cooperative and competitive networks. Similar to regression methods, ERGMs provide a parameter estimate and standard error for each configuration. The standard error is used to assess the statistical significance of the configuration (Lusher et al, 2014). However, they differ from linear regression methods in that they take into consideration multiple structure parameters (also referred to as overlapping and nested building blocks) (Lusher et al, 2014). To disentangle the influence of each building block, and avoid convergence issues, it is possible to develop simple models that take each configuration incrementally, making sure that convergence is reached at each step (Lusher et al, 2014). To test which network structure leads to greater tie formation within the tankers' cooperative and competitive network, we analyze three network properties: reciprocity, clustering, and homophily (**Table 26**). We build our ERGMs using the R statnet, sna and ergm packages (Handcock et al. 2008).

Table 26 - Exponential Random Graph Models.

Hypothesis	**SNA Nomenclature**	**Model Parameter**	**R statnet Function**	**Description and Network Structure**

		Base Density	edge	The model looks at the density parameter of both networks and helps assess whether ties have a random and uniform distribution.
Hypothesis 2 Type of tie	Bonding Ties	**Model 1** Density + Reciprocity	mutual	Building on the base model and looks at propensity of tie reciprocation between cooperating and competing informal tankers and is an indication of bonding tie formation (within subgroup ties), (Robbins and Lubell, 2020).
Hypothesis 2 Type of tie	Bonding Ties	**Model 2** Density + Triangles	gwesp[1]	Building on the base model through the addition of alternating triangle configuration. Triangles refer to ties between any two stakeholders sharing the same third neighbor (Henry & Vollan, 2014). This helps identify clustering, cohesion and bonding tie formation (within subgroup ties), (Berardo 2014).
Hypothesis 1b Similar Characteristics	Religious Homophily	**Model 3** Density + Triangles + Religion Homophily	nodematch.religion[2]	Building on model 2 through the addition of a religious homophily parameter. Homophily refers to the formation of ties among actors sharing similar characteristics (Henry et al 2011). This model looks at whether religion, influences the propensity of informal tankers forming ties with other informal tankers when they are cooperating and competing.
Hypothesis 1b Similar Characteristics	Religious Homophily	**Model 4** Density + Triangles + Religion Homophily + Religious Type	nodematch.religion[2] nodefactor.religion.m[3] nodefactor.religion.c[3]	Building on model 3 through the addition of a religious type parameter. This model looks which religious group tends to form more ties for each cooperative and competitive network.

[1] To avoid model degeneration, we use the geometrically weighted edgewise shared partner distribution (gwesp), (Hunter 2007). Two nodes (i, j) are considered to have edgewise shared partner (ESP) if they are both connected to each other and they are also connected to a common third node (k). Closer nodes have a higher likelihood to connect and close triangulation, compared to further nodes. The gwesp function takes into consideration this processes through its decay parameter. A high decay parameter of 1 indicate that only closer ties can connect and close their triangles (a connection among three actors). We chose our values for model convergence considerations.

[2] To identify religious homophily we use the function nodematch and label it as *nodematch.religion*.

[3] To identify which religion type has a higher tendency to form a ties, we use the function nodefactor. The label *nodefactor.religion.c* , is used to refer to actors belonging to the Christian group, and *nodefactor.religion.m* , is used to refer to actors belonging to the Muslim group.

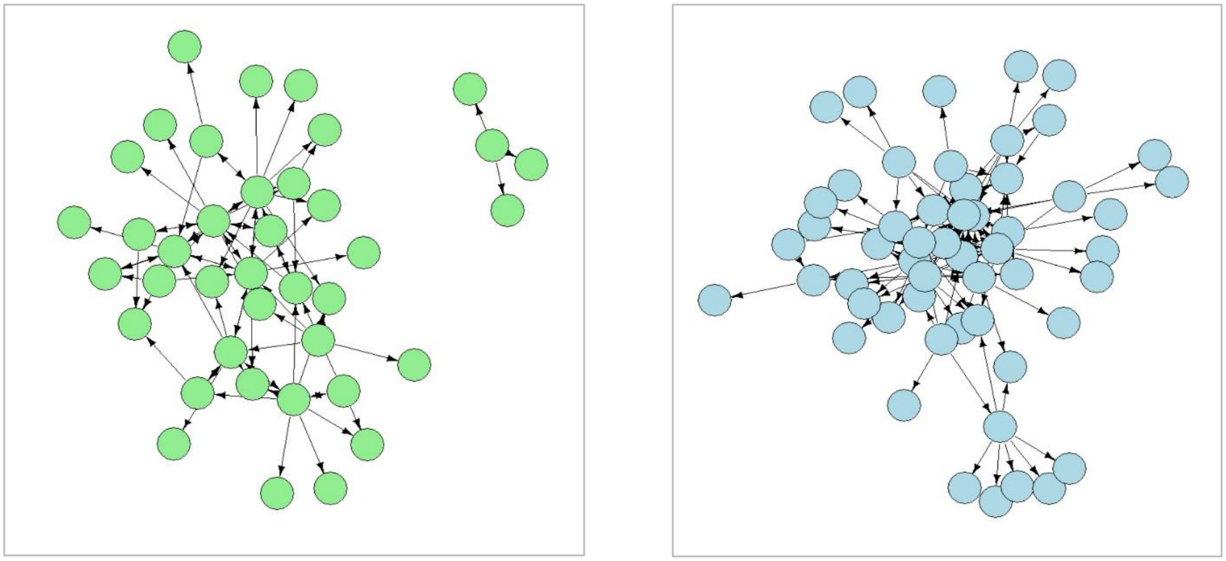
Results

This section compares results for the cooperative and competitive networks. It starts with presenting both networks. It then goes through the networks' descriptive analysis at three levels and subsequently, shows the ERGMs.

Cooperative and Competitive Networks

Figure 15 shows both the cooperative (in green left side) and competitive (in blue right side) networks of informal water tankers. The figures illustrate the basic structure of the social network among informal water tankers. Each colored point represents an informal water tanker, and the lines between them represent their connection (tie). The connections are directed showing the source of the connection and targeted connection. The network visuals were generated using the *network* function from the ergm package in R (Handcock et al. 2008). The descriptive analysis below unpacks each network at different macro, meso and micro levels.

Figure 15 - Cooperative (in green on the left) and Competitive (in blue on the right) Networks.



Descriptive Social Network Analysis

Macro-Level

The macro-level analysis (**Table 27)** indicated that density values (proportion of observed ties relative to all possible ties), for both networks, are very low, with ratios of 0.05 and 0.04 for the cooperative and competitive networks respectively, indicating that neither network is dense. These very low densities are less than would be randomly expected. This might be linked to the small size of networks, a constraint which is further discussed in the limitation section.

Overall the competitive network is larger with 54 nodes and 378 ties, compared to the cooperative network with 39 nodes and 316 ties. The competitive network also has smaller and shorter paths, with a smaller diameter and mean distance of 5 and 1.99 respectively, compared to the cooperative network with a diameter of 6 and a mean distance of 2.69.

Assortativity quantifies the extent to which connections are influenced by a stakeholders' religion. The cooperative network has higher assortativity values with 43%, whereas the competitive network's assortativity value is almost inexistent with 1%. Those that share same religion tend to form more ties in the cooperative network, so those that have the same religion, tend to cooperate.

Reciprocity identifies the proportion of ties reciprocated among two tanker businesses and it indicates bonding ties (Putnam 2000). The cooperative network has higher reciprocity values with 37%, compared to the competitive network, which has almost no reciprocity of ties with 1.7%, indicating more bonding ties in the cooperative network.

Table 27 - Macro Level Analysis Results.

		Cooperative Network	**Competitive Network**
Network Density		0.05	0.04
Network Size	Number of Nodes	39	54
	Number of Degrees	316	378
	Average Degrees	4.15	4.33
	Network Diameter	6	5
	Network Mean Distance	2.69	1.99

Network Assortativity	0.43	0.01
Network Reciprocity	0.37	0.017

To explore religious diversity, for each network, we looked at overall percentages of Christians and Muslims nodes and their outgoing ties (**Table 28**). We focus on outgoing ties for two reasons. First, our data collection method asked stakeholders to point out with whom they are connected, so we recorded outgoing ties. And the number of outgoing ties tends to represent key individuals (Lusher et al, 2014). Generally, there are more Christian nodes than Muslim nodes in both networks. The cooperative network has 71% Christian nodes and 28% Muslim nodes, compared to 67% Christian nodes and 33% Muslims nodes for the competitive network. So we would expect more outgoing ties from Christian nodes. In the cooperative network 83% of outgoing ties involve Christian nodes and in the competitive network, 89% of the outgoing ties involve Christian nodes.

Even though there are more Christian nodes in general, when we look at the outgoing ties and node to node religion type, this Christian dominance differs between the networks. In the cooperative network, the Christian dominance still persists with 82% of outgoing ties from Christian to Christian node, and 57% from Muslim to Christian nodes. However, this is not the case in the competitive network. Outgoing ties seemed to be balanced between Muslim and Christian nodes with 50% of outgoing ties from Christian to Christian nodes and Christian to Muslim nodes. Also, 46% of outgoing ties are from Muslim to Muslim nodes and 54% are from Muslim to Christian nodes. In the competitive network, religion type does not seem to have a role in forming outgoing ties. The likelihood to develop an outgoing competitive relationship with a Christian node or Muslim node is roughly the same.

Table 28 - Percentage of Outgoing Ties by Religion Type.

	Cooperative Network	**Competitive Network**
Nodes		
Number of Christian Nodes	71%	67%
Number of Muslim Nodes	28%	33%
Total Outgoing Ties		

Christian Nodes Total Outgoing Ties	83%	89%
Muslim Nodes Total Outgoing Ties	17%	11%
Outgoing Ties per Religion		
Christian Node to Christian Node	82%	50%
Christian Node to Muslim Node	18%	50%
Muslim Node to Muslim Node	43%	46%
Muslim Node to Christian Node	57%	54%

Meso-Level

Meso-level results in **Table 29** show both networks have low modularity values and many subgroups. indicating that both networks are fragmented. The smaller competitive network has 1.5 times more subgroups with a total of 32, compared to the cooperative network with 19 subgroups. Nevertheless, the cooperative network has double within group ties than the competitive network, shown by their modularity values, measured at 14% and 7% respectively.

The cooperative network has a smaller largest clique and a smaller core with 6 and 5 nodes respectively, compared to the competitive network with a largest clique of 7 nodes and a core of 9 nodes. This is likely to be linked to the size of networks. Since the competitive network is larger with more nodes and ties (from the macro-level analysis), it also has a larger core and largest clique. Moreover, since coreness and largest cliques represent subgroups with high numbers of ties, the competitive network has subgroups composed of more nodes that are better connected.

Table 29 - Meso Level Analysis.

	Cooperative Network	**Competitive Network**
Modularity	0.14	0.0742
Number of Subgroups	19	32
Largest Clique: number of nodes	6	7
Core: number of nodes	5	9

The qualitative results in **Table 30** and **Table 301** show that for the largest clique and core the nodes of the cooperative network are 100% Christians operating for an average of 40 years. Whereas the nodes of the competitive network are more religiously diverse (around 40% of the nodes are Muslim) and have been operating for around 22 years. The number of trucks per firm does not differ between the two networks; the average number is 9 - 10 trucks.

Table 30 - Largest Clique Nodes Characteristics.

Coded Names	Religion	Year of Operation	Number of Trucks
Cooperative Network			
sk	Christian	58	2
chr	Christian	61	6
pr	Christian	31	8
bch	Christian	21	20
ab	Christian	51	7
Average	**100% Christian**	**44**	**9**
Competitive Network			
mww	Muslim	7	14
amw	Muslim	7	14
co	Muslim	12	8
rac	Christian	31	12
mar	Christian	11	10
ab	Christian	51	7
pr	Christian	31	8
Average	**43% Muslim and 57% Christian**	**21**	**10**

Table 31 - Core Nodes Characteristics.

Coded Names	Religion	Year of Operation	Number of Trucks
Cooperative Network			
ab	Christian	51	7
pr	Christian	31	8
bch	Christian	21	20
chr	Christian	61	6
sk	Christian	58	2
Average	**100% Christian**	**44**	**9**
Competitive Network			
sa	Christian	3	1
bm	Muslim	NA	NA
chr	Christian	61	6
co	Muslim	12	8
pr	Christian	31	8
mw	Muslim	7	14
amw	Muslim	7	14
mar	Christian	11	10
ab	Christian	51	7
Average	**40% Muslim and 60% Christian**	**24**	**9**

Micro-Level

The identified key individuals and their characteristics are presented in **Table 32** in order of centrality (**Appendix II-Table 36** has a complete list of attributes). Key individuals from cooperative and competitive networks have four similarities. They have similar average number of ties (14 for the cooperative network and 15 for the competitive network). They are all in the Northern suburbs and serve different areas in Beirut. They access, roughly, the same number of wells (2 for the cooperative network and 3 for the competitive network). And their well ownership status is also mixed. In terms of religious diversity, key individuals are mainly Christian. The cooperative networks' key individuals are slightly less diverse with four Christians and one Muslim compared to two Muslim in the competitive network. This Christian dominance can be linked to the overall presence of more Christian nodes in both networks. Key individuals mainly differ in the following. Cooperative network members have been 1.7 times longer in the market, but have fewer trucks (with an average of 37 years and 9 trucks, compared to an average of 21 years and 11 trucks).

Table 32 - Key individuals and attributes.

Key Individuals	Rank Order	Religion	Years of operation	Total number of Trucks	Total Number of Ties
Cooperative Network					
bch	1	Christian	21	20	15
chr	2	Christian	61	6	16
sk	3	Christian	58	2	15
pr	4	Christian	31	8	12
co	5	Muslim	12	8	11
Average			**37**	**9**	**14**
Competitive Network					
mar	1	Christian	11	10	15
rac	2	Christian	31	12	19
amw	3	Muslim	5	14	13
mww	4	Muslim	5	14	13
ab	5	Christian	51	7	16
Average			**21**	**11**	**15**

*did not interview, and data was inferred from other interviews. This also explain their zero outgoing ties.

ERGMs

The base ERGM model includes only the edge parameter, which tests network density. The cooperative and competitive networks have negative and high magnitudes of -2.8505 and -3.1554, respectively. This indicates that the probability to forming a tie in both networks is very low, for the cooperative network it is 0.054[5] and for the competitive network it is 0.04[6]. These results show both networks are rather sparse.

Model 1 focuses the reciprocity parameter, which indicates bonding ties (within subgroup connections) (Robbins and Lubell, 2020). The results indicate reciprocity is statistically significant for the cooperative network only, with a p value smaller than 0.001. The reciprocity estimation parameter indicates that cooperative businesses have a 93% probability[7] of reciprocating a tie with another business already connected to them.

Model 2 focuses on triangle structures in the network (or triads), which indicate bonding ties (within subgroup connections) (Berardo, 2014). The results show both networks have high triangle structures with around 80%[8] likelihood to form a triangle structure. Both networks have a propensity for clustering and bonding tie formation.

Model 3 includes a religious homophily parameter that identifies whether religion influences the propensity of stakeholders forming ties with other stakeholders. It indicates that religious homophily is only significant in the cooperative network where cooperative stakeholders have a 61%[9] likelihood to form a tie with another stakeholder of the same religion.

Model 4 looks at which religion group has a higher likelihood to form a tie. The results indicate that for both the cooperative and competitive network, religion type is not statically significant since p values are higher than 0.05.

Table 33 - Exponential Random Graph Models Results for the Cooperative Network.

	Parameter	**Parameter Estimation**	**Standard Error**
Base			
General Parameter: density	edges	-2.8505 ***	0.1143

---

[5] Probability of the edges estimation parameter -2.8505 is (exp (-2.8505)/ (1+ exp (-2.8505))

[6] Probability of the edges estimation parameter -3.1554 (exp (-3.1554)/ (1+ exp -3.1554))

[7] based on the reciprocity value of the cooperative network of 2.7405: and calculated as (exp (2.7405)/ (1+ exp 2.7405).

[8] based on the triangles values of the cooperative and competitive network of 1.6097 and 1.3898, respectively and calculated as (exp (1.6097)/ (1+ exp 1.6097)) and (exp (1.3898)/ (1+ exp 1. 1.3898)) respectively.

[9] based on the reciprocity value of the cooperative network of 0.4860: and calculated as (exp (0.4860)/ (1+ exp 0.4860).

Model 1			
Density	edges	-3.2737 ***	0.1483
+ Reciprocity	mutual	2.7405***	0.3835
Model 2			
Density	edges	-3.8754 ***	0.1606
+ Triangles	gwesp (0.01)	1.6097 ***	0.16097
Model 3			
Density	edges	-4.1574 ***	0.1923
+ Triadic Closure	gwesp (0.01)	1.5610 ***	0.1656
+ Homophily (religion)	nodematch.religion	0.4860 **	0.1786
Model 4			
Density	edges	-3.66255 ***	0.41165
+ Triadic Closure	gwesp (0.01)	1.51072 ***	0.17421
+ Homophily (religion)	nodematch.religion	0.04719	0.37996
+ Religion Type	nodefactor.religion.m	-0.39525	0.30618

$P < 0.05$ *
$P < 0.01$ **
$P < 0.001$***

Table 34 - Exponential Random Graph Models Results for the Competitive Network.

	Parameter	**Parameter Estimation**	**Standard Error**
Base			
General Parameter: density	edges	-3.1554 ***	0.0944
Model 1			
Density	edges	-3.1288 ***	0.0986
+ Reciprocity	mutual	-0.8897	0.9420
Model 2			
Density	edges	-3.8575 ***	0.1197
+ Triangles	gwesp (0.03)	1.3898 ***	0.1255
Model 3			
Density	edges	-3.853352 ***	0.144004
+ Triadic Closure	gwesp (0.03)	1.394348 ***	0.121161
+ Homophily (religion)	nodematch.religion	-0.0009914	0.159600
Model 4			
Density	edges	-3.862847 ***	0.2022726
+ Triadic Closure	gwesp (0.03)	1.384131 ***	0.129686
+ Homophily (religion)	nodematch.religion	-0.001857	0.201785
+ Religion Type	nodefactor.religion.m	0.010383	0.106393

$P < 0.05$ *
$P < 0.01$ **
$P < 0.001$***

These models are tested by Goodness of Fit (GOF) statistics. This helps assess whether models are converging properly and whether the models are “a good fit” and “resemble” the base model and observed data. Our GOF are limited at reproducing the parameters in the models and we plot them as box plots (quantiles) of the simulated sampler. To have a good fit, the observed statistics should be near the sample median (0.5). Models often fail to converge, and in many cases it is necessary to adjust the MCMC (Markov chain Monte Carlo) control parameters. For our models we changed the MCMC interval to reduce autocorrelation problems and increase the number of proposals between sampled statistics to reach a good fit for the different models (see **Appendices VI** and **VII)**.

Discussion

This study uses a Social Network Analysis (SNA) approach to identify the network of informal water tanker businesses in Beirut (Lebanon) and analyze drivers and aspects of their cooperative and competitive relationships. Cooperation is defined as working amicability together, communicating or helping each other over clients, maintenance of trucks, wells, and/or prices. Competition is defined as having had an argument, conflict or fight over the same issues. Cooperation and competition can happen simultaneously or might change over time. However, our analysis only includes the dominant type of interaction that was recorded during the time of the interview. Cooperation and competition can affect informal tankers’ behavior and type of information shared between them.

We have three main findings. 1) Cooperation and competition are influenced by the business owner’s religion and years in the market. 2) The cooperative network is smaller with more inner subgroup connections, and the competitive network is larger and with mixed inner and across subgroup connections. 3) Collaboration and or competition can determine the type of information exchanged – businesses cooperate for nonessential information and compete for restricted information. The discussion ends with implications of cooperation and competition on end-users and the overall water system.

Key individuals and Characteristics

Key individuals that cooperate and compete are distinct. Generally, they share similar characteristics such as size (number of tankers), number of wells, location and service area. However, two main differing characteristics, religion and years in the market, influence cooperation and competition in different ways. Religion seems important in forming ties for the cooperative network. Key individuals, of this network, are mainly Christian, whereas the competitive network's key individuals are 40% Muslim stakeholders. Cooperating with those of similar religion is not surprising. Businesses generally prefer to create connections with those of similar characteristics or beliefs (Henry et al 2011). However, this can lead to "us and them" attitude (Borgatti and Foster, 2003), where Christian stakeholders emphasize their own identity (Barnes-Mauthe et al., 2013) connecting only with other Christian stakeholders. This was perceivable in the qualitative interviews:

> *"We* [the Christians] *were the first ones to distribute water. Today anyone can own a water tanker. In West Beirut* [Muslim Area], *there were almost no trucks at all. The competition with the Muslims has increased a lot. They do business in a different and more aggressive way, they are ready to reduce the cost of the service and reduce their profit margin."* – SK (Christian, operating for 58 years).

The second main difference is that cooperative stakeholders have been twice as long in the market (an average of 40 years in operation), compared to the competitive network (an average of 20 years in operation). Trust can emerge from a history of interaction (Robbins and Lubell, 2020), and cooperation is higher among older operating stakeholders. The correlation between new market entries and the increase of competition was evident in the qualitative interviews. Twelve of the twenty interviewees mentioned that the informal water market has changed in the last few years, and that the competition and number of tankers has generally increased, mainly after the years of 2013 and 2015:

> *"I have been in the businesses for more than 30 years, and since I started the demand of water tankers has increased by 5 folds."* – CHJ, (Christian, operating for 31 years).

> *"Since I started this business, the situation has completely changed with an increase of competition."* – EAJ, (Christian, operating for 11 years).

These years coincide with recent droughts in Lebanon and the region (Gray, 2016; Sarant, 2021). This correlation suggests a local effect of climate change. The increase of droughts has increased household water intermittence and the demand of informal water tankers. This has led to the proliferation of informal water tankers and to an increase of competition.

> "*There was a boom in the trucking businesses after 2014, which was a very dry winter. There was so much work that the business did not stop during that year except for the month of March."*– PR, (Christian, operating for 31 years).

Network Size, Network Ties and Type of Information

The competitive network is larger, with more nodes and ties, indicating more competition among informal water tankers. The cooperative network is smaller with higher levels of inner subgroup connections. High level of internal connections can sometimes result from high risk situations (Berardo and Scholz, 2010). For example, sometimes when stakeholders are in high risk situations or under stress, they tend to generate more ties with those that they already trust, instead of connecting with external new stakeholders, hence they increase their overall internal links (Berardo, 2014). This could be the case for the old informal tankers facing growing competition and perceive new firms as a risk to their business. This new risk pushes older tankers to form ties with other older tankers that they already trust, hence this increases their overall internal trust. This sense of threat was noticeable is the interviews:

> *"The increase of competition has decreased my work by 70%"* – AS, (Muslim, operating for 20 years).
>
> *"The situation is only going backwards because of the increase of competition"* – IS, (Christian, operating for 21 years).
>
> *"They* [informal water tankers] *help each other out by kicking out a new tanker that is coming to the neighborhood"* – PR, (Christian, operating for 31 years).

However, the shortcomings of only developing internal connections is that when stakeholders only connect within a network, they become isolated from their surroundings (Alexander et al 2018). This isolation is noticeable in the cooperative network, as it is less diverse, with its predominant composition of Christian stakeholders.

We found no religious correlation between business ownership and service areas (geographic location of customers), even though, in the SNA field, geography has been analyzed as a factor that improves tie formation among actors (examples include Alexander et al (2018) and Robbins and Lubell, (2020)). In our case, geography and religion are closely linked (**Map 7**) and informal suppliers are always seeking new clients to increase their revenues regardless of clients' religion and always ready to expand into new geographic areas.

The competitive network has a mix of inner and across subgroup connections. Developing different types of ties is not unusual, and indicates capacity to develop simultaneous solutions for different types of problems (Berardo, 2014). Through their different connections, competitive tankers can connect with (religiously) diverse subgroups. External connections usually help stakeholders acquire new information (Berardo and Lubell, 2016). Competitive tankers acquire information on market price and new service areas, as indicated in our qualitative interviews:

> *"We do not communicate with them [other water tankers] but the game is mainly about price wars and steeling clients. By driving around we can notice when the same truck is parked and emptying at the same spot. We usually talk either with the building owner or the caretaker to know about the price. We usually offer lower prices and sometimes the customer changes tankers, other time they don't and stick to the original tankers."* – RAC, (Christian, operating for 31 years).

Collaboration and or competition can determine the type of information exchanged among businesses (Barnes et al., 2017). In our case, we noticed two types of information: restricted and nonessential.

Restricted information, including price and service areas, increase with competition, as mentioned above. Nonessential information, including service quality and truck maintenance increase with collaboration. This was evident in some of our interviews:

> *"When one tanker is down they* [other collaborative stakeholders] *call me to keep the client happy and make sure not to lose them."* – PR, (Christian, operating for 31 years).
>
> *"We usually talk about vehicle inspections, maintenance and tankers"* – GHN, (Christian, operating for 27 years).

Cooperating and competing over type of information is also evident in other case studies. For example, Barnes et al (2017) found that fishermen cooperate and exchange long-term information related to technical innovations, whereas they are more careful with short-term information related to location of species. The type of information exchanged depends on the economic gain from this information (Barnes et al., 2017). Similar to this example, our result show the type of information shared is based on economic gains. Informal water tankers easily share information with low economic gains, such as service quality and truck maintenance, and are more careful sharing information leading to high economic gains such as market price and service areas.

Key Takeaways

In Beirut, the network of informal water tankers is changing. Christian informal water businesses have cooperated for more than 40 years. With recent droughts, the network is seeing new, religiously diverse businesses, that have started to break the old informal water market. Competitive stakeholders are more religiously diverse, they can acquire new and restricted market information (sometimes through violent behavior) to secure a dominant position. Competition is, however, double-sided. For water access, competition might benefit end-users to lower the tanker water price. Generally, informal water sources cost "4 to 30 times" more than municipal water (Wutich et al, 2016). Moreover, from chapter 2, 87% of a Lebanese household's water budget goes to informal sources (including tankers, bottles, and wells), and informal tankers take up to 4% of that budget. This study shows that competition is breaking the old informal water market, and this also has reduced water prices for households. Further research on informal market prices is needed to confirm this suggestion. From a resource perspective, competition can lead to the “tragedy of a commons” situation related to groundwater exploitation (Ostrom, 2008). Mismanagement, poverty and corruption (Rogers & Hall, 2003), coupled with increased drought events (Gray, 2016; Sarant, 2021) will likely expand informal water tanker businesses. In return, these businesses will continue pumping and distributing groundwater in an unmonitored and informal way, which will exacerbate existing seawater intrusion (Alameddine et al 2018). Further research also is needed to track the interdependence of groundwater quality and the informal water tanker network.

Study Limitations

The study’s main limitation is the number of interviews conducted, and relatedly, the overall network size that could be elaborated for analysis. Due to political instability in the area during the data collection period, the study was limited to a small number of stakeholders who were willing to take part in the interviews. We could not identify any official or non-official list of informal water businesses, so we did not know the size of the network prior to data collection. Future research on informal networks, should take these limitations into account and extend data collection periods to be able to develop networks with a greater number of nodes and ties. Small network sizes might explain the networks’ low densities. Having a small number of nodes and ties might also have affect the ERGMs results. ERGMs are best fitted when total network size is known. Under sampling is a common problem identified in other types of research projects (Shalizi and Rinaldo, 2013). Finally, religion is a sensitive topic in the country. Hence, it was not possible to directly ask interviewees about their religion. This was inferred from their names, and this process might have been inaccurate impacting the results obtained in the assortativity and homophily parameters.

Conclusion

Through a Social Network Analysis (SNA) approach, we identify and characterize the network of informal water tankers in Beirut (Lebanon), study their relationships and understand their impacts on end-users and water sources. In Beirut, cooperation and competition among informal water tankers is shaped by religion type, number of operating years, and type of exchanged information. Old Christian stakeholders that try to maintain cooperative relationships face a new threat. New market entries, composed of religiously diverse competitors, are breaking this old market. While cooperation usually happens around nonessential information such as service quality and truck maintenance, competitors can access restricted information, such as prices charged and service areas, because of their mixed types of ties. Their entry also coincides with recent droughts in Lebanon and the region, indicating a local effect of climate change. Competition is double sided. It reduces market prices, making water more accessible to end-users. However, it also can lead to the tragedy of common groundwater from over-pumping.

References

Adam, S., & Kriesi, H. (2007). The network approach. *Theories of the policy process*, *2*, 189-220.

Ahlers, R., Cleaver, F., Rusca, M., & Schwartz, K. (2014). Informal space in the urban waterscape: Disaggregation and co-production of water services. *Water Alternatives*, 7(1), 1-14.

Alameddine, I., Tarhini, R., & El-Fadel, M. (2018). Household economic burden from seawater intrusion in coastal urban areas. *Water International*, *43*(2), 217–236.

Alexander, S. M., Bodin, Ö., & Barnes, M. L. (2018). Untangling the drivers of community cohesion in small-scale fisheries. *International Journal of the Commons*, *12*(1), 519–547.

Amit, R. K., & Sasidharan, S. (2019). Measuring affordability of access to clean water: A coping cost approach. *Resources, Conservation and Recycling*, *141*, 410–417.

Angst, M., & Fischer, M. (2020). Identifying Subsystems and Crucial Actors in Water Governance: Analysis of Bipartite Actor—Issue Networks. In *Networks in Water Governance*. (pp. 115-143). Palgrave Macmillan.

Ansell, C., & Gash, A. (2007). Collaborative Governance in Theory and Practice. *Journal of Public Administration Research and Theory*, *18*(4), 543–571

Baerveldt, C., Van Duijn, M. A., Vermeij, L., & Van Hemert, D. A. (2004). Ethnic boundaries and personal choice. Assessing the influence of individual inclinations to choose intra-ethnic relationships on pupils' networks. *Social Networks*, *26*(1), 55-74.

Bakker, K., Kooy, M., Shofiani, N. E., & Martijn, E. J. (2008). Governance failure: rethinking the institutional dimensions of urban water supply to poor households. *World Development*, 36(10), 1891-1915.

Balazs, C. L., & Lubell, M. (2014). Social learning in an environmental justice context: a case study of integrated regional water management. *Water Policy*, 16(S2), 97-120.

Barnes, M., Kalberg, K., Pan, M., & Leung, P. (2016). When is brokerage negatively associated with economic benefits? Ethnic diversity, competition, and common-pool resources. *Social*

Networks, *45*, 55–65.

Barnes, M. L., Arita, S., Kalberg, K., & Leung, P. (2017). When does it pay to cooperate? Strategic information exchange in the harvest of common-pool fishery resources. *Ecological Economics*, *131*, 1–11.

Barnes-Mauthe, M., Arita, S., Allen, S. D., Gray, S. A., & Leung, P. (2013). The Influence of Ethnic Diversity on Social Network Structure in a Common-Pool Resource System: Implications for Collaborative Management. *Ecology and Society*, *18*(1), art23.

Basurto, X., Blanco, E., Nenadovic, M., & Vollan, B. (2016). Integrating simultaneous prosocial and antisocial behavior into theories of collective action. *Science Advances*, *2*(3), e1501220.

Bavelas, A. (1950). Communication patterns in task-oriented groups. *The journal of the acoustical society of America*, *22*(6), 725-730.

Berardo, R. (2009). Processing Complexity in Networks: A Study of Informal Collaboration and its Effect on Organizational Success. *Policy Studies Journal*, *37*(3), 521–539.

Berardo, R. (2014). The evolution of self-organizing communication networks in high-risk social-ecological systems. *International Journal of the Commons*, *8*(1), 236.

Berardo, R., Alcañiz, I., Hadden, J., & Jasny, L. (2016). *Networks and the Politics of the Environment* (J. N. Victor, A. H. Montgomery, & M. Lubell, Eds.; Vol. 1). Oxford University Press.

Berardo, R., & Lubell, M. (2016). Understanding What Shapes a Polycentric Governance System. *Public Administration Review*, *76*(5), 738–751.

Berardo, R., & Scholz, J. T. (2010). Self-Organizing Policy Networks: Risk, Partner Selection, and Cooperation in Estuaries: SELF-ORGANIZING POLICY NETWORKS. *American Journal of Political Science*, *54*(3), 632–649.

Bodin, Ö. (2017). Collaborative environmental governance: Achieving collective action in social-ecological systems. *Ecological Systems*, 10.

Bodin, Ö., Alexander, S. M., Baggio, J., Barnes, M. L., Berardo, R., Cumming, G. S., Dee, L. E., Fischer, A. P., Fischer, M., Mancilla Garcia, M., Guerrero, A. M., Hileman, J., Ingold, K., Matous, P., Morrison, T. H., Nohrstedt, D., Pittman, J., Robins, G., & Sayles, J. S. (2019). Improving network approaches to the study of complex social–ecological interdependencies. *Nature Sustainability*, *2*(7), 551–559.

Bodin, Ö, Crona, B. I., & Ernstson, H. (2006). Social Networks in Natural Resource Management: What Is There to Learn from a Structural Perspective? *Ecology and Society*, 9.

Bodin, Ö, & Crona, B. I. (2008). Management of Natural Resources at the Community Level: Exploring the Role of Social Capital and Leadership in a Rural Fishing Community. *World Development*, *36*(12), 2763–2779.

Bodin, Ö, & Crona, B. I. (2009). The role of social networks in natural resource governance: What relational patterns make a difference? *Global Environmental Change*, *19*(3), 366–374.

Bodin, Ö, Mancilla García, M., & Robins, G. (2020). Reconciling Conflict and Cooperation in Environmental Governance: A Social Network Perspective. *Annual Review of Environment and Resources*, *45*(1), 471–495.

Borgatti, S. P. (2005). Centrality and network flow. *Social Networks*, *27*(1), 55–71.

Borgatti, S. P., Everett, M. G., & Johnson, J. C. (2018). *Analyzing social networks*. Sage.

Borgatti, S. P., & Foster, P. C. (2003). The network paradigm in organizational research: A review and typology. *Journal of management*, *29*(6), 991-1013.

Boucquey, N. C. (2016). Actors and audiences: negotiating fisheries management. *Journal of Environmental Policy & Planning*, *18*(4), 426-446.

Cheng, D. (2014). The Persistence of Informality: Small-Scale Water Providers in Manila's Post-Privatisation Era. *Water Alternatives*, *7*(1).

Christian-Smith, J., Balazs, C., Heberger, M., & Longley, K. (2013). Assessing water affordability. *A pilot study in two regions of California, Pacific Institute.*

Chua, V., J. Madej, and B. Wellman. 2011. Personal Communities: The World According to Me. In *The SAGE Handbook of Social Network Analysis*, eds. J. Scott and P. Carrington, 101–115. Thousand Oaks, CA: SAGE Publications Inc.

Csardi, G., & Nepusz, T. (2006). The igraph software package for complex network research. *InterJournal, complex systems*, *1695*(5), 1-9.

Cisneros, P. (2019). What makes collaborative water governance partnerships resilient to policy change? A comparative study of two cases in Ecuador. *Ecology and Society*, *24*(1).

Coleman, J. S. (1988). Social capital in the creation of human capital. *American journal of sociology*, *94*, S95-S120.

Crona, B., & Bodin, Ö. (2006). What You Know is Who You Know? Communication Patterns Among Resource Users as a Prerequisite for Co-management. *Ecology and Society*, *11*(2), art7.

Crona, B., Ernstson, H., Prell, C., Reed, M., & Hubacek, K. (2011). Combining social network approaches with social theories to improve understanding of natural resource governance. *Social networks and natural resource management: uncovering the social fabric of environmental governance*, 44-72.

Collignon, B., & Vézina, M. (2000). Independent water and sanitation providers in African cities. *World Bank, Water and Sanitation Program, Washington, DC.*

Constantine, K., Massoud, M., Alameddine, I., & El-Fadel, M. (2017). The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of Environmental Management*, *188*, 85-94.

Damonte, G. H. (2019). The constitution of hydrosocial power. *Ecology and Society*, *24*(2).

de Lange, E., Milner-Gulland, E. J., & Keane, A. (2019). Improving Environmental Interventions by Understanding Information Flows. *Trends in Ecology & Evolution*, *34*(11), 1034–1047.

Easter, K. W., Rosegrant, M. W., & Dinar, A. (2018). *Formal and informal markets for water: institutions, performance, and constraints* (pp. 393-410). Routledge.

Ebrahimiazarkharan, F., Ghorbani, M., Malekian, A., & Bressers, H. T. A. (2020). Analyzing Stakeholders' Network to Water Resources Co-management at a Watershed Scale: A Case Study from the Taleghan Watershed in Iran. In *Networks in Water Governance*. (pp. 203-238). Palgrave Macmillan.

Eklund, J. F., & Cabeza-Jaimejuan, M. D. M. (2017). Quality of governance and effectiveness of protected areas: crucial concepts for conservation planning. *Annals of the New York Academy of Sciences*.

El-Fadel, M., Maroun, R., Semerjian, L., & Harajli, H. (2003). A health-based socio-economic assessment of drinking water quality: The case of Lebanon. *Management of Environmental Quality: An International Journal*, *14*(3), 353–368.

Emerson, K., Nabatchi, T., & Balogh, S. (2012). An Integrative Framework for Collaborative Governance. *Journal of Public Administration Research and Theory*, *22*(1), 1–29.

Eppstein, D., Löffler, M., & Strash, D. (2010). Listing all maximal cliques in sparse graphs in near-optimal time. In *International Symposium on Algorithms and Computation* (pp. 403-414). Springer, Berlin, Heidelberg.

Etikan, I. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1.

Faour, M. A. (2007). Religion, demography, and politics in Lebanon. *Middle Eastern Studies*, *43*(6), 909-921.

Freeman, L. C., Roeder, D., & Mulholland, R. R. (1979). Centrality in social networks: II. Experimental results. *Social networks*, *2*(2), 119-141.

Fischer, M., & Ingold, K. (2020). Conceptual Reflections About Water, Governance, and Networks. In *Networks in Water Governance*. (pp. 17-49). Palgrave Macmillan.

Fischer, M., & Sciarini, P. (2016). Drivers of collaboration in political decision making: A cross-sector perspective. *The Journal of Politics*, *78*(1), 63-74.

Girvan, M., & Newman, M. E. (2002). Community structure in social and biological networks. *Proceedings of the national academy of sciences*, *99*(12), 7821-7826.

Gray, E. (2016). NASA Finds Drought in Eastern Mediterranean Worst of Past 900 Years. *Retrieved*, *25*, 2018.

Handcock, M. S., Hunter, D. R., Butts, C. T., Goodreau, S. M., & Morris, M. (2008). statnet: Software tools for the representation, visualization, analysis and simulation of network data. *Journal of statistical software*, *24*(1), 1548.

Hanneman, R. A., & Riddle, M. (2005). Introduction to social network methods.

Henry, A. D., & Vollan, B. (2014). Networks and the Challenge of Sustainable Development. *Annual Review of Environment and Resources*, *39*(1), 583–610.

Henry, A. D., Lubell, M., & McCoy, M. (2011). Belief systems and social capital as drivers of policy network structure: The case of California regional planning. *Journal of public administration research and theory*, *21*(3), 419-444.

Herzog, L. M. J., & Ingold, K. (2020). Collaboration in Water Quality Management: Differences in Micro-Pollutant Management Along the River Rhine. In *Networks in Water Governance*. (pp. 203-238). Palgrave Macmillan.

Hunter, D. R. (2007). Curved exponential family models for social networks. *Social networks*, *29*(2), 216-230.

Ingold, K., Driessen, P. P. J., Runhaar, H. A. C., & Widmer, A. (2018). On the Necessity of Connectivity: Linking Key Characteristics of Environmental Problems with Governance Modes. *Journal of Environmental Planning and Management*, online.

Izady, M. M. (2020). Urban unplanning: how violence, walls, and segregation destroyed the urban fabric of Baghdad. *Journal of Planning History*, *19*(1), 52-68.

Janssen, M. A., Bodin, Ö., Anderies, J. M., Elmqvist, T., Ernstson, H., McAllister, R. R. J., Olsson, P., & Ryan, P. (2006). Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems. *Ecology and Society*, *11*(1), art15.

Janssen, M.A., Ostrom, E., (2006). *Inequality, Cooperation and Environmental Sustainability*. Princeton University Press, pp. 60–96.

Jepson, W., Budds, J., Eichelberger, L., Harris, L., Norman, E., O'Reilly, K., ... & Stoler, J. (2017a). Advancing human capabilities for water security: a relational approach. *Water Security*, 1, 46-52.

Jepson, W., & Vandewalle, E. (2016). Household water insecurity in the global north: a study of rural and periurban settlements on the Texas–Mexico Border. *The Professional Geographer*, *68*(1), 66-81.

Jepson, W. E., Wutich, A., Colllins, S. M., Boateng, G. O., & Young, S. L. (2017b). Progress in household water insecurity metrics: a cross-disciplinary approach. *Wiley Interdisciplinary Reviews: Water*, 4(3), e1214.

Kjellén, M., & McGranahan, G. (2006). *Informal water vendors and the urban poor* (pp. 978-1). London: International Institute for Environment and Development.

Komarulzaman, A. (2017). *Water affordability, water quality and their consequences for health and education in Indonesia* (Doctoral dissertation, Radboud Repository of the Radboud University, Nijmegen, the Netherlands).

Kudva, N. (2009). The Everyday and the Episodic: The Spatial and Political Impacts of Urban Informality. *Environment and Planning A: Economy and Space*, *41*(7), 1614–1628.

Liddle, E. S., Mager, S. M., and Nel, E. L. (2016). The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *The Geographical Journal*, 182(1), 85–96.

Lienert, J., Schnetzer, F., & Ingold, K. (2013). Stakeholder analysis combined with social network analysis provides fine-grained insights into water infrastructure planning processes. *Journal of Environmental Management*, *125*, 134–148.

London, J. K., Fencl, A. L., Watterson, S., Choueiri, Y., Seaton, P., Jarin, J., ... & Bailey, C. (2021). Disadvantaged Unincorporated Communities and the Struggle for Water Justice in California. *Water Alternatives*, *14*(2), 520-545.

Lusher, D., Kremer, P., & Robins, G. (2014). Cooperative and Competitive Structures of Trust Relations in Teams. *Small Group Research*, *45*(1), 3–36.

Lynch, B. D. (2012). Vulnerabilities, competition and rights in a context of climate change toward equitable water governance in Peru's Rio Santa Valley. *Global Environmental Change*, *22*(2), 364-373.

Mancilla García, M. M., & Bodin, Ö. (2019). Participatory water basin councils in Peru and Brazil: Expert discourses as means and barriers to inclusion. *Global Environmental Change*, *55*, 139-148.

Maloy, T. K. (2017, November) Reports reveal pollution, profit-making from water trucks. *Annahar. Retrieved* from https://www.annahar.com/english/article/694564-aub-researchers-report-pollution-and-proand-profitmaking-from-tankers-delivering

Mancilla Garcia, M., & Bodin, Ö. (2020). What Drives the Formation and Maintenance of Interest Coalitions in Water Governance Forums?. In *Networks in Water Governance*. (pp. 145-172). Palgrave Macmillan.

Mancilla García, M., Hileman, J., & Bodin, Ö. (2019). Collaboration and conflict in complex water governance systems across a development gradient: Addressing common challenges and solutions. *Ecology and Society*, *24*(3), art28.

Marsden, P. 2011. Survey Methods for Network Data. In *The SAGE Handbook of Social Network Analysis*, eds. J. Scott and P. Carrington, 370–388. Thousand Oaks, CA: SAGE Publications Inc.

Masuda, Y. J., Liu, Y., Reddy, S. M. W., Frank, K. A., Burford, K., Fisher, J. R. B., & Montambault, J. (2018). Innovation diffusion within large environmental NGOs through informal network agents. *Nature Sustainability*, *1*(4), 190–197.

McGinnis, M. D., & Ostrom, E. (2014). Social-Ecological System Framework: Initial Changes and Continuing Challenges. *Ecology and Society*, *19*(2), 30.

Moore, E., Matalon, E., Pacific Institute (Oakland, Calif.), Community Water Center, Clean Water Fund (Washington, D. C.), & California Rural Legal Assistance Foundation. (2011). *The human costs of nitrate-contaminated drinking water in the San Joaquin Valley*. Pacific Institute. http://www.pacinst.org/reports/nitrate_contamination/nitrate_contamination.pdf

Newman, M. E. (2002). Assortative mixing in networks. *Physical review letters*, *89*(20), 208701.

Newman, M. E. (2006). Modularity and community structure in networks. *Proceedings of the national* *academy of sciences*, *103*(23), 8577-8582.

Newman, M. E., & Girvan, M. (2004). Finding and evaluating community structure in networks. *Physical review E*, *69*(2), 026113.

Nastiti, A., Sudradjat, A., Geerling, G. W., Smits, A. J. M., Roosmini, D., & Muntalif, B. S. (2017). The effect of physical accessibility and service level of water supply on economic accessibility: A case study of Bandung City, Indonesia. *Water International*, *42*(7), 831–851.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., & Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, *44*, 358–366.

Ostrom, E. (2008). Tragedy of the commons. *The new palgrave dictionary of economics*, *2*.

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change*, 19(3), 354-365.

Pardos, A., (June 8, 2006) "CRS Issue Brief for Congress: Lebanon". The Library of Congress. Retrieved August 11, 2020.

Pattanayak, S. K., Yang, J.-C., Whittington, D., & Bal Kumar, K. C. (2005). Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal: COPING WITH UNRELIABLE PUBLIC WATER SUPPLIES. *Water Resources Research*, *41*(2).

Peloso, M., & Morinville, C. (2014). 'Chasing for Water': Everyday Practices of Water Access in Peri-Urban Ashaiman, Ghana. *Water Alternatives*, *7*(1).

Poteete, A. R., & Ostrom, E. (2004). Heterogeneity, group size and collective action: The role of institutions in forest management. *Development and change*, *35*(3), 435-461.

Prados, A. (2006). *Lebanon.* CRS Issue Brief for Congress

Putnam, R. D. (2000). *Bowling alone: The collapse and revival of American community*. Simon and Schuster.

Ramirez-Sanchez, S. (2007). *A social relational approach to the conservation and management of fisheries: the rural communities of the Loreto Bay National Marine Park, BCS,* *Mexico* (Doctoral dissertation, School of Resource and Environmental Management-Simon Fraser University).

Rank, O. N. (2008). Formal structures and informal networks: Structural analysis in organizations. *Scandinavian Journal of Management*, *24*(2), 145-161.

Robins, G., Bates, L., & Pattison, P. (2011). Network governance and environmental management: conflict and cooperation. *Public Administration*, *89*(4), 1293-1313.

Robbins, M., & Lubell, M. (2020). Network Segregation and Water Governance: The Case of the Spiny Lobster Initiative. In *Networks in Water Governance*. (pp. 51-85). Palgrave Macmillan.

Rogers, P., and Hall, W. (2003). Effective Water governance. In *GWP Technical Committee Background Papers No. 7*. Global Water Partnership, Stockholm.

Roy, A. (2005). Urban Informality: Toward and Epistemology of Planning. *Journal of the American Planning Aoosication*, 71(2), 147-158.

Sandström, A., & Rova, C. (2009). The network structure of adaptive governance-A single case study of a fish management area. *International Journal of the Commons*, *4*(1).

Sarant, L. (2021, April 27). MENA drought: *Tackling drought in Jordan, Lebanon and Morocco*. International Water Management Institute. https://www.iwmi.cgiar.org/2020/03/menadrought-tackling-drought-in-jordan-lebanon-and-morocco/

Seidman, S. B. (1983). Network structure and minimum degree. *Social networks*, *5*(3), 269-287.

Schneider, M., Scholz, J., Lubell, M., Mindruta, D., & Edwardsen, M. (2003). Building consensual institutions: networks and the National Estuary Program. *American journal of political science*, *47*(1), 143-158.

Schulz, C., Martin-Ortega, J., Ioris, A. A., & Glenk, K. (2017). Applying a 'Value Landscapes Approach'to conflicts in water governance: the case of the Paraguay-Paraná Waterway. *Ecological economics*, *138*, 47-55.

Schwartz, K., Tutusaus Luque, M., Rusca, M., & Ahlers, R. (2015). (In) formality: the meshwork of water service provisioning. *Wiley Interdisciplinary Reviews: Water*, *2*(1), 31-36.

Scott, J. (1988). Social network analysis. *Sociology*, *22*(1), 109-127.

Shaban, A. (2021). Rivers of Lebanon: Significant Water Resources under Threats. In *Hydrology*. IntechOpen.

Shalizi, C. R., & Rinaldo, A. (2013). Consistency under sampling of exponential random graph models. *Annals of statistics, 41*(2), 508.

Solo, T. M. (1999). Small-scale entrepreneurs in the urban water and sanitation market. *Environment and urbanization*, *11*(1), 117-132.

Stein, C., Ernstson, H., & Barron, J. (2011). A social network approach to analyzing water governance: The case of the Mkindo catchment, Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, *36*(14–15), 1085–1092.

Swyngedouw, E. (2006). Circulations and Metabolisms: (Hybrid) Natures and (Cyborg) Cities. *Science as Culture* 15 (2):105-122.

Swyngedouw, E. (2005). Governance innovation and the citizen: The Janus face of governance-beyond-the-state. *Urban studies*, *42*(11), 1991-2006.

Swyngedouw, E. (2004). *Social Power and the Urbanisation of Water. Flows of Power.* Oxford: Oxford University Press.

Team, R. C. (2013). R: A language and environment for statistical computing.

Walter, C. T., Kooy, M., & Prabaharyaka, I. (2017). The role of bottled drinking water in achieving SDG 6.1: An analysis of affordability and equity from Jakarta, Indonesia. *Journal of Water, Sanitation and Hygiene for Development*, 7(4), 642-650.

Wasserman, S., & Faust, K. (1994). Social network analysis: Methods and applications.

Wutich, A., Beresford, M., & Carvajal, C. (2016). Can informal water vendors deliver on the promise of a human right to water? Results from Cochabamba, Bolivia. *World Development*, *79*, 14-24.

Young, S. L., Collins, S. M., Boateng, G. O., Neilands, T. B., Jamaluddine, Z., Miller, J. D., ... & Schuster, R. C. (2019). Development and validation protocol for an instrument to measure household water insecurity across cultures and ecologies: the Household Water InSecurity Experiences (HWISE) Scale. *BMJ open*, 9(1), bmjopen-2018.

Appendix I – Network Characteristics

Table 35 – Appendix I: Network Characteristics and Water Governance (Positive and Negative) Outcomes.

Characteristics	Context	Positive Outcomes	Negative Outcomes	Author
Centrality and Key individuals				
Centrality	Multi-stakeholder governance of a small river basin in Argentina	• Central and popular actors solve coordination problems.		Berardo, (2014)
Centrality	Governance structure of spiny lobster fishery	• Centralized leaders can help the formation of new ties and facilitate coordination as they can distribute information efficiently.		Robbins and Lubell, (2020)
Centrality	Bi-partite network: actors involved in water politics in Swiss national and cantonal level + Water-related issues	• Actors within and between systems acts as connectors with knowledge on management and organization of resources.		Angst and Fischer, (2020)
Centrality Cohesion	Multi-governance process of private and public agencies of Mkindo catchment, Tanzania	• High within community ties leads to collaboration. • Presence of brokerage and leadership.	• Information flows among few actors only.	Stein et al, (2011)
Centrality Fragmentation	Governance process of administrative and jurisdiction actors in the micro pollutant management of the Rhine river	• Central actors are scientists and authorities, mainly because the problem at core is very technical.	• Network fragmentation makes policy outcomes difficult.	Herzog and Ingold, (2020).
Centrality Cohesion	Interaction among fishing communities in Hawaii	• Being well connected locally increases economic productivity.	• Lack of trust across groups raises suspicion for those who interact across groups. • Brokerage has a negative effect because of high	Barnes et al (2016)

			level of competition. • Over embeddedness can have a negative effect on economic outcomes.	
Centrality Cohesion	Interaction among fishing communities in Hawaii	• Being well connected locally is positively associated with productivity.	• Exchanging information among different social divides does not result in a positive economic outcome.	Barnes et al (2017)
Fragmentation	Water management of four communities in rural regions of Zürich		• Horizontal fragmentation and vertical fragmentation.	Lienert et al, (2013)
Homophily				
Homophily	Coalitions that participate in water governance forums	• Actors coordinate when they share similar visions, when they are from the same sector (mainly private), and the main state.	• Diversity makes groups less included to coordination.	Mancilla Garcia and Bodin, (2020)
Homophily	Communication network of rural fishermen in coastal Kenya	•	• Gear type homophily inhibits exchange of ecological knowledge.	Crona and Bodin, (2006)
Geographic Proximity	Local leaders and key actors involved in water resources management of Taleghan Watershed	• Higher cooperation in upper stream area.	• Low level of trust, and low level of cooperation. Unwillingness to connect with stakeholders from other regions.	(Ebrahimiazarkharan et al, (2020
Homophily	Interaction of small-scale fisheries in Jamaica	• Connecting with actors of the same fishing gear and same landing site.		Alexander et al (2018)
Homophily Geographic Proximity	Governance structure of spiny lobster fishery	• Geographic and sectorial homophily.		Robbins and Lubell, (2020)
Ethnic Homophily	Fisheries in Hawaii	• Creates ties with external leaders	Impacts collaboration across groups	Barnes-Mauthe et al. (2013)

Bonding and Bridging ties				
Bonding and Bridging ties	Multi-stakeholder governance of a small river basin in Argentina	• Combination of bonding and bridging structures helps networks develop simultaneous solutions of different problem types.	• High risk situation leads to high level of bonding ties and triadic structure.	Berardo, (2014)
Bonding and Bridging ties	Self-organizing policy arenas in 10 U.S. estuaries	Bridging ties appear in less risk environments mainly by connecting actors with other distant in the network.	• Bonding ties appear when actors are under risk mainly to detect and punish uncooperative behavior.	Berardo and Scholz, (2010)
Bonding and Bridging ties	Complex governance systems of different institutions	• Bonding social capital is more valuable for overlapping information. • Bridging social capital is valuable for the acquisition of new information for innovation.		Berardo and Lubell, (2016)
Bridging ties	Rural coastal communities accessing fish resources in Baja California Mexico	• Bridging helps locate fish stock abundance.		Ramirez-Sanchez (2007)
Bridging ties	Governance of multiple estuary networks	• Boundary spanning actors of different groups had a positive effect on trust, beliefs and collaboration.		Schneider et al (2003)
Bonding	Governance structure of spiny lobster fishery	• Reciprocity and transitivity are both positive for network closure and bonding social capital.		Robbins and Lubell, (2020)
Density				
Density Homogenization	Interaction of rural Fishermen in Kenya	• Social capital leads to an unwillingness to report rule breaking, showing a form of collaboration.	• Homogeneity reduces the ability to synthesize new information.	Bodin and Crona (2008)
Density Fragmentation Homophily	Interaction of small-scale fisheries in Jamaica	• Denser network results with increased social cohesion.	• Increased bonding ties can lead to isolated actors.	Alexander et al (2018)
Density Homogenization	Multi-organizational projects solving water-related problems in southwest Florida	• Increasing number of actors results positively with increased access to funding.	• Added nodes might lead to exchange of redundant information.	Berardo (2009)

Density Homogenization	Governance process of multiple private and public actors within a fish management area in Sweden	- Increased number of direct and indirect links facilitate the ability to solve conflict and improve rule forming.	- Increased density can reduce heterogeneity and knowledge diversity.	Sandström and Rova, (2009)

Appendix II – Types of Networks

SNA has been applied to understand the relationship of stakeholders in different types of networks as presented in **Table 36**. These include networks comprised of stakeholders from formal public and private institutions (Berardo, 2009; Sandström and Rova, 2009; Angst and Fischer 2020) that can be further subdivided into categories such as level of involvement in decision-making (Berardo and Scholz, 2010; Berardo and Lubell, 2016), representation of high-income areas (Berardo, 2009; Sandström and Rova, 2009; Angst and Fischer 2020), and representation of lower-income areas (Berardo, 2014; Robbins and Lubell, 2020; Mancilla Garcia and Bodin 2020). We can also classify networks of self-organized individuals, such as networks of fishermen (Bodin and Crona, 2008; Alexander et al., 2018; Barnes et al 2016; Barnes et al 2017) whose interactions operate under local jurisdiction but may also be affected by international conservation measures (Barnes et al 2017). Networks may also be formed by a mix of stakeholders that connect local communities with formal institutions. For example, local leaders may sometimes be more engaged with local water resources issues (Ebrahimiazarkharan et al, 2020), and their involvement in decision making processes can help address these issues. In other cases, they may have direct access to formal agencies, educational institutions and financial mechanisms, and thus, play a key role by connecting local communities with these formal institutions (Bodin, and Crona, 2008). Finally, a less researched category of networks may be connections between informal stakeholders (Stein et al 2011). Within network science, informality, has mainly focused on how informal ties enable the transfer of new information within organizations (e.g. Rank, 2008; Borgatti, 2005; Putnam, 2000; Berardo, 2009; Masuda et al 2018). In our application, we are referring to non-state stakeholders (Adam and Kreisi, 2007) that operate in complete autonomy (Stein et al., 2011). This study focuses on informal stakeholders, and takes Lebanon as a case study.

Table 36 - Types of Networks.

	Network Description	Location	Reference

Stakeholders within Formal Institutions	Range of governmental and non-governmental actors that are formally recognized, including coalitions, boards, associations, public administrative, universities, organization, community actors and indigenous groups.	Florida, USA Sweden Switzerland Argentina Honduras Brazil	Berardo (2009) Sandström and Rova (2009) Angst and Fischer (2020) Berardo, (2014) Robbins and Lubell, (2020) Mancilla Garcia and Bodin (2020)
Self-Organized Stakeholders	Fishermen.	Kenya Jamaica Hawaii	Bodin and Crona (2008) Alexander et al (2018) Barnes et al (2017) and Barnes et al (2016)
Stakeholders Mix Type	Hidden population of local leaders and key actors that impact water resources management.	Iran	Ebrahimiazarkharan et al (2020)
	Relationship of local leaders with formal institution and their impact on the management of rural fishing community.	Kenya	Bodin and Crona (2008)
Non-State and Informal Stakeholders	Traditional and locally agreed, non-codified actors such as village leaders.	Tanzania	Stein et al. (2011)
	Water Vendors	Bolivia	Wutich et al. (2016)

Appendix III – Collaboration and competition.

Within environmental governance, SNA literature has usually focused on the advantages of collaboration and its positive impact on governance. Collaborative approaches generally promote engagement among stakeholders (Ansell and Gash 2007; Emerson et al 2012). Increased social interaction improves social capital by building trust among stakeholders, sharing norms, and creating community bonds (Coleman, 1988; Putnam, 2000). In turn, increased social capital increases social learning (Henry and Vollan, 2004; Crona et al, 2011), which helps the development of collective actions to resolve environmental problems (Ansell and Gash 2007; Emerson et al 2012; de Lange et al, 2019; Pahl-Wostl, 2009; Balazs & Lubell; 2014) and achieve desired social and environmental outcomes (Eklund & Cabeza 2017).

Collaboration does not always lead to significant systemic behavioral and environmental change (Bodin, 2017). In some cases, multi-stakeholder interactions may be conflictual (Mancilla Garcia et al 2019; Bodin et al 2020) and conflicts may arise for a range of different reasons (see summary in **Table 37**). One driver of conflict might be a situation where one or more stakeholder group(s) are (or are perceived to be) marginalized. This occurred in a case in Ecuador, where a change in policy limited the participation of previously influential nongovernmental organizations (Cisneros, 2019). There also might be issues over the control of the resource. For example, powerful agribusiness coalitions may overexploit groundwater resources, as evidenced by a case on the Peruvian coast (Damonte, 2019) and a conflict around the Paraguay-Paraná Waterway in Brazil (Schulz et al 2017). In some cases, administrative goals are unclear or inconsistent, such as the case in Swedish island of Gotland where the municipal government struggled between balancing economic development by expanding mining and preserving water quality (Mancilla Garcia et al., 2019). Conflict also can rise over water quality and quantity issues and geographic control, such as in the case of Peru’s Rio Santa, where competition is centered around economic and jurisdictional interests in upstream and downstream parts of the river (Lynch, 2012).

In some situations, collaboration and conflict (with a focus on competition) can happen simultaneously (Bodin et al 2020; Mancilla Garcia, 2019). Although this is less popular in the literature, Bodin et al (2020) summarize a number of cases of the co-occurrence of collaborative and competitive interests, as referred to in **Table 37**. For example, a highly competitive situation can ultimately lead to cooperation, as occurred in the small-scale fisheries of Baja California (Basurto et al, 2016) and the red drum fishery in North Carolina (Boucquey, 2016). In other cases, this happens by chance, such as with the Swan River in Western Australia (Robins et al 2011).

Table 37 - Case studies highlighting Conflict and Co-Occurrence of Cooperation and Competition.

Conflict, Cooperation and Competition	Context	Location	Reference
Unsuccessful collaborations that leads to conflict	Stakeholder participation manipulation and limiting nongovernmental organization participation.	Ecuador	(Cisneros, 2019)
	Control of resources and overdraft of groundwater pumping.	Peruvian coast	(Damonte, 2019)
		Brazil	(Schulz et al 2017)
	Unclear administrative goals.	Swedish island of Gotland	(Mancilla Garcia et al., 2019)
	Water quality and quantity control by upstream and downstream actors.	Peru	(Lynch, 2012)
Drivers that lead to co-occurrence of cooperation and competition	Highly competitive situations can result in cooperation.	Baja California	(Basurto et al, 2016)
	Reaching a compromise.	North Carolina	(Boucquey, 2016)
	Unplanned agreement.	Western Australia	(Robins et al 2011)

Appendix IV – Descriptive Analysis: three levels

Macro-level

For each cooperative and competitive network, macro-level analysis is based on network density & size, centrality, assortativity and reciprocity.

- Density is the proportion of observed ties compared to all theoretically possible ties in the network (Fischer and Ingold 2020). High density increases opportunities of interactions and information exchange (Janssen and Ostrom, 2006; Bodin and Crona, 2009), and this can increase social cohesion (Bodin and Crona, 2008; Alexander et al, 2018).
- Size takes into account total number of nodes (stakeholders) and ties, diameter and mean distance. The diameter[10] is the longest shortest path in the network, and the mean distance[11] is the average length of the shortest path between two stakeholders. When diameter and mean distance are small, stakeholders are better connected and more integrated, hence information can travel faster.
- Assortativity[12] shows whether stakeholders with similar attributes connect to each other (Newman 2002). In our case study we look specifically at whether religion plays a role in tie formation. If assortativity coefficient is high, then religion is an attribute that influences tie formation.
- Reciprocity indicates the proportion of ties that are reciprocated among two stakeholders (Putnam 2000, Berardo and Scholz 2010). Higher level of reciprocity shows higher level of interaction

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[10] The diameter is identified by calculating all shorted paths between two nodes and then choosing the longest one.

[11] The mean distance is the shortest path between all pairs of nodes and adding them and dividing by the total number of pairs.

[12] The function *assortativity nominal* is a coefficient that quantifies the extent to which connected stakeholders share similar properties by measuring the correlation between every pair of stakeholders that are connected. It is defined as: $r=(sum(e(i,i), i) - sum(a(i)b(i), i)) / (1 - sum(a(i)b(i), i))$, where $e(i,j)$ is the fraction of edges connecting vertices of type i and j, $a(i)=sum(e(i,j), j)$ and $b(j)=sum(e(i,j), i)$, (based on Newman, (2002)).

thus higher network stability (Wasserman and Faust 1994). For our case study, it is taken as an indirect measure for bonding ties (Robbins and Lubell, 2020).

Meso-level

Networks tend to be composed of multiple subgroups or clusters. Clusters occur when some nodes have more connections (densely connected) with each other, than with others in the network (Fischer and Ingold 2020). The number of subgroups influences the level of network cohesion. A high number of subgroup indicates some level of network fragmentation, which slows information transfer between all members of the network (Fischer and Ingold 2020).

- We use the function cluster_edge_betweenness13 (Newman & Girvan, 2004). The function calculates the total number of subgroups and the modularity of the network. The concept of modularity has been used to quantify and measure the proportion of ties that occur within communities, relative to the expected proportion if all ties were placed randomly (Newman, 2006; Girvan & Newman 2002; Newman & Girvan 2004). Thus, high level of modularity indicates density within group connections and sparse ties across groups (Newman, 2006; Fischer and Ingold 2020; Robbins and Lubell 2020), which is an indication of bonding ties.

To identify the most influential subgroups we look at those with the highest number of ties through two functions.

- The function k-core decomposition14 helps identify stakeholders with a specific number of ties. For our case study we look for stakeholders with a highest number of ties hence we identify those that tend to be at the core of the network (Csardi and Nepusz, 2006)

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[13] The function *cluster edge betweeness* measures the number of shorted paths in the network. Edges (or ties) connecting separate subgroups have a high edge betweenness because all the shortest paths, from one subgroup to another, must traverse through them. How it works is that it removes the edge (tie) with the highest edge betweenness score, then recalculating edge betweeness of the edges, and again removing the one with the highest score, etc… (based on Newman & Girvan, (2004)).

[14] The k-core of a network is a subgroup in which all nodes have at least (k) level of ties. All nodes having (k+1) ties, then they do not belong to this subgroup, (based on Seidman, (1983)).

- The function largest clique[15] identifies the largest subgroup of nodes that are directly connected to every other node within this subgroup (based on Eppstein et al 2010). Those with more ties have a higher level of influence, because of their high number of connections.

Micro-level

For both cooperative and competitive networks, we identify key individuals by first measuring, and then ranking the nodes' four centrality criteria: degree centrality, betweenness, closeness, and eigenvector:

- Degree centrality calculates the number of direct connection that a stakeholder has. A high degree centrality indicates that a stakeholder has more direct connection than other stakeholders (Scott 1988; Freeman et al 1979; Borgatti 2005), hence a higher level of direct influence.
- Betweeness centrality[16] refers to the degree to which an stakeholder connects other stakeholders who would otherwise not be connected. Nodes with high betweenness can fill structural holes and are important bridging stakeholders, or brokers, connecting different subgroups in the network (Freeman et al 1979; Borgatti 2005; Boding and Crona, 2009). They connect different parts of the network and their removal might lead to network fragmentation.
- Closeness centrality[17] indicates how close a stakeholder is to all other stakeholders in the network (Bavelas, 1950). High closeness score shows that the stakeholder has the shortest distance to all other stakeholders, hence they are able to easily connect and spread information in the network.

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[15] A clique is a fully connected subgroup. Hence, the largest clique presents the largest fully connected subgroup of stakeholders.

[16] This is calculated with the following formula $g(v) = \sum_{s \neq t \neq v} \frac{\sigma_{st}(v)}{\sigma_{st}}$ where σ_{st} is the total number of shortest paths from node *s* to node *t* and $\sigma_{st}(v)$ is the number of those paths that pass through *v*, (based on Freeman, (1977)).

[17] This is the average shortest distance from each stakeholder to each other stakeholders. It is calculated as the inverse of the average shortest distance between the stakeholders and all other stakeholders in the network such as $C(x) = \frac{1}{\sum_y d(y,x)}$, where *d(y,x)* is the distance between the nodes *x* and *y*, (based on Bavelas, (1950)).

- Eigenvector centrality18 takes into account not only the connection of stakeholders, but whether they are connected to important stakeholders too (for example those with high number of ties). Hence if a stakeholder is connected to many important stakeholders, they will also be important in the network. A high eigenvector score indicates that a stakeholder is connected to many important other stakeholders in the network (Newman, 2006).

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[18] To measure the eigenvector centrality of a node, we first measure the centrality score of each node its connected to. The centrality score should be proportional to the sum of the scores of all nodes which are connected to this node. Hence this allows us to measure whether this node is connected to other important nodes. To calculate this we use the equation $x_i = \frac{1}{\lambda} \sum_{j \in M(i)} x_j$ where $j \in M(i)$ means that the sum is over all j such that the nodes i, j are connected.

Appendix V – Key individuals and Characteristics

Table 38 – Appendix II: Key individuals and complete list of attributes.

Key Individuals	Rank Order	Religion	Years of operation	Total number of Trucks	Well Ownership	Number of Wells	Well Quality	Location	Service Area	Outgoing Ties	Incoming Ties	Total Number of Ties
Cooperative Network												
bch	1	Christian	21	20	Owner	1	Good	Suburb North	All Beirut	8	7	15
chr	2	Christian	61	6	Owner	2	Poor	Suburb North	All Beirut	9	7	16
sk	3	Christian	58	2	Owner	1	Poor	Suburb North	All Beirut	11	4	15
pr	4	Christian	31	8	Owner	3	Good	Suburb North	All Beirut	5	7	12
co	5	Muslim	12	8	Renting	1	Good	Suburb North	All Beirut	7	4	11
Average			**37**	**9**		**2**				**8**	**6**	**14**
Competitive Network												
mar	1	Christian	11	10	Renting	NA	Good	Suburb North	All Beirut	9	6	15
rac	2	Christian	31	12	Owner	2	Good	Suburb North	All Beirut	14	5	19
amw*	3	Muslim	5	14	NA	NA	NA	Suburb North	All Beirut	0	13	13
mww*	4	Muslim	5	14	NA	NA	NA	Suburb North	All Beirut	0	13	13
ab	5	Christian	51	7	Renting	3	Good	Suburb North	All Beirut	16	0	16
Average			**21**	**11**		**3**				**8**	**7**	**15**

Appendix VI – Goodness of Fit of the Cooperative Network

Figure 16 - Goodness of Fit of Network Density

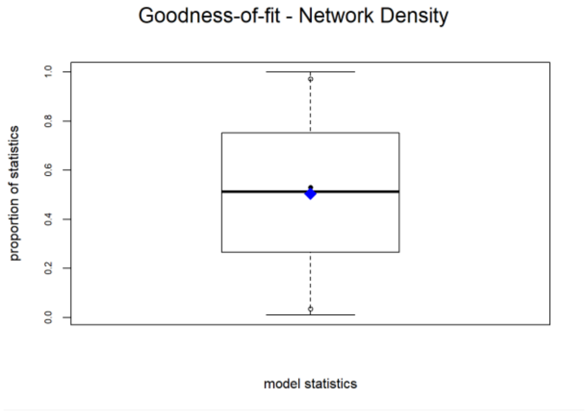


Figure 17 - Goodness of Fit of Network Reciprocity

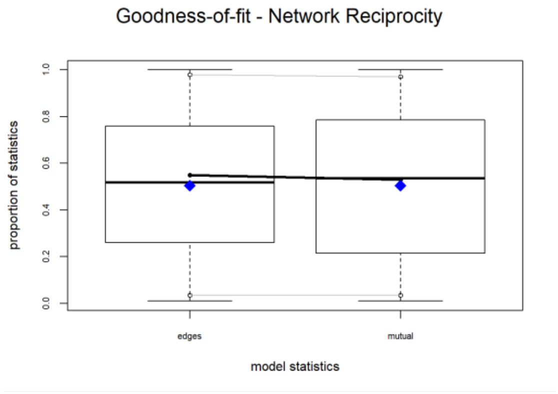


Figure 18 - Goodness of Fit of Network Triangle

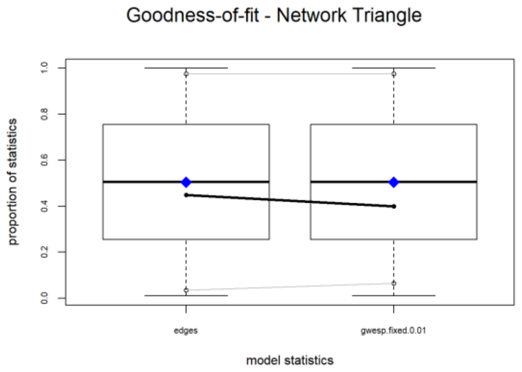


Figure 19 - Goodness of Fit of Network Homophily

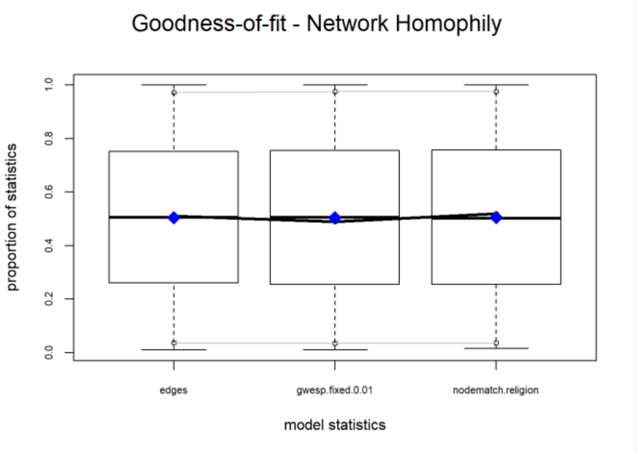
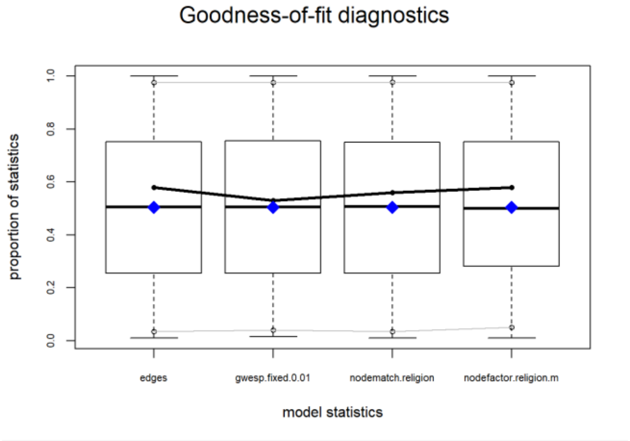


Figure 20 - Goodness of Fit of Network Religious Type



Appendix VII – Goodness of Fit of the Competitive Network

Figure 21 - Goodness of Fit of Network Density

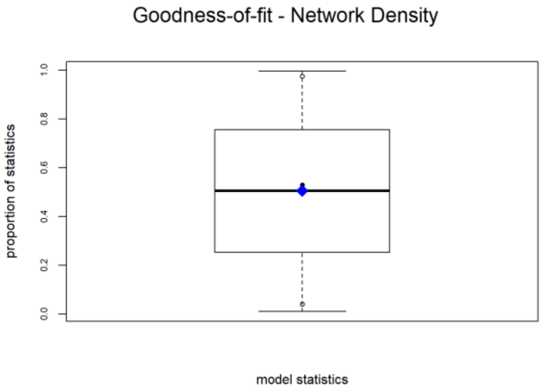


Figure 22 - Goodness of Fit of Network Reciprocity

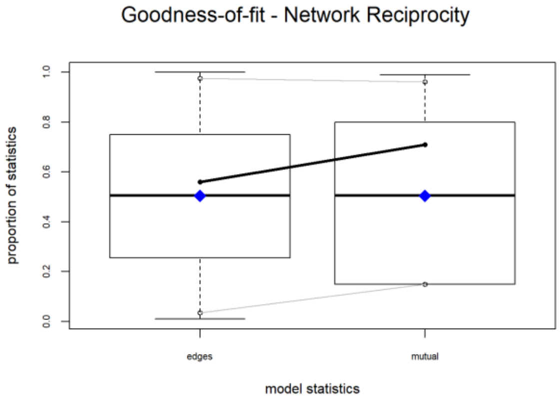


Figure 23 - Goodness of Fit of Network Triangle

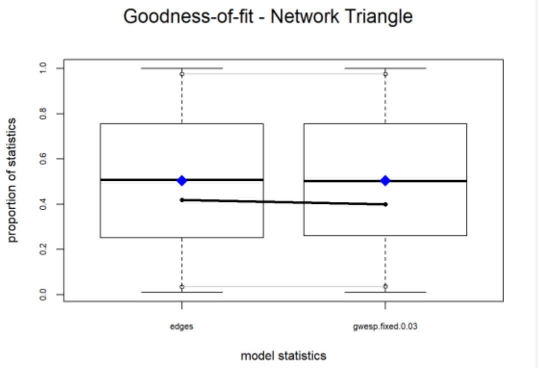


Figure 24 - Goodness of Fit of Network Homophily

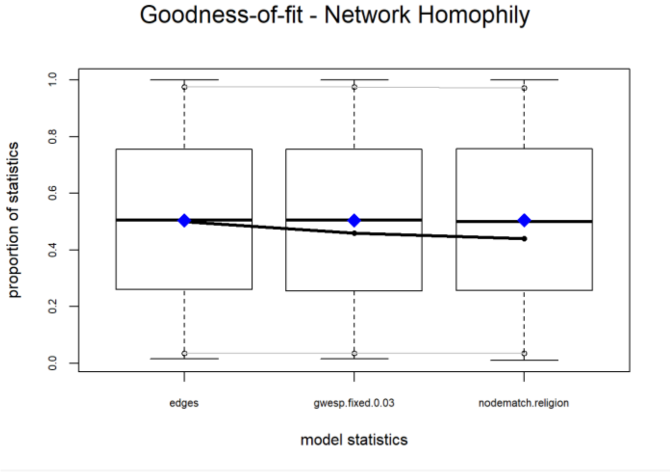
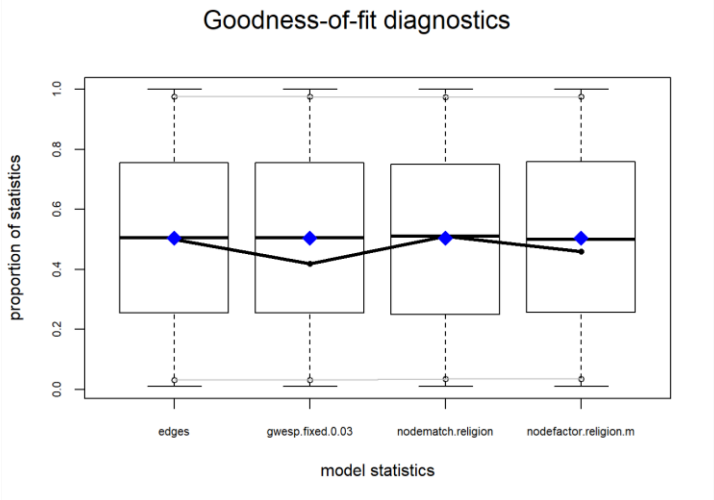


Figure 25 - Goodness of Fit of Network Religious Type



Chapter 5: Overall Discussion and Conclusions

In many areas in the world have piped water supplies is insufficient in quantity, quality, or reliability, so individuals and communities acquire different informal sources including water delivered through tanker trucks, bottled water, or pumping water from local wells to satisfy their daily water needs. This research assesses informal water systems in Beirut (Lebanon). It provides a qualitative and empirical analysis of the affordability disparities of such systems, their energy requirements and carbon emissions, and the stakeholders behind Beirut's informal water systems. The research contributes methodologically to fields of water affordability, energy-water nexus and Social Network Analysis (SNA). Theoretically, it also contributes to the fields of political ecology and water justice. We conclude that: 1) informal water systems are indirectly influenced by socio-cultural and environmental drivers that impact how informal stakeholders control and manage resources. 2) Access to informal sources is not homogenous across communities, with lower-income communities facing larger risks and resulting with socio-economic disparities. 3) Even when informal sources are a small portion of the water supply, their socio-economic and environmental impacts are still very significant. And 4) informal systems are complex and interwoven with formal piped infrastructure. So we propose hybrid recommendations that do not seek to solely support or eliminate informal systems, but rather suggest opportunities to attenuate their negative impacts.

Methodological Contributions

The affordability of water supply systems has been an issue for engineers and planners over many centuries. Typical affordability studies tend to focus on people's access to piped drinking water. Rare are the frameworks that evaluate the cost and affordability of accessing multiple water sources (Nganyanyuka et al., 2014; Teodoro, 2018), or capture water affordability of different income groups with a focus on lower income (Nastiti et al., 2017; Komarulzaman, 2017; Thompson et al., 2001; Jepson and Vandewalle, 2016; Pattanayak et al., 2005). Chapter 2 contributes to this field by combining these two lines of frameworks: we identify water affordability disparities of informal sources by taking into account the cost of both formal (piped infrastructure) and informal water sources for both high and low- income communities.

From an environmental perspective, we question the sustainability of informal water systems by assessing their environmental impact, focusing on their energy-water nexus and carbon emissions. While nexus studies have evolved to account for different environmental dimensions of energy within water systems (Spang et al 2020), they largely focus on centralized formal piped water services and neglect to address informal services (Hamiche et al. 2016). Chapter 3 contributes and expands the field by considering the energy use and carbon emissions of informal water sources. The chapter analyzes energy use and carbon emissions per cubic meter of water; and total energy use and carbon emissions per capita in the study region considering total water delivery volumes per source.

Understanding the organization and interaction of informal stakeholders is challenging and has rarely been researched because of the nature of their informality, i.e. their hidden characteristics and lack of regulation (Bakker et al., 2008). Chapter 4 uses a Social Network Analysis (SNA) approach to identify Beirut’s informal water tankers and characterize their relationships. SNA method is typically used to study patterns of social connections among stakeholders of formal institutions and organizations (Berardo, 2009; Sandström and Rova, 2009; Angst and Fischer 2020), and aspects of their collaboration (Bodin et al 2020; Mancilla Garcia et al., 2019). We advance this field by studying an informal network, and by exploring the socio-cultural drivers behind simultaneous collaborative and competitive of informal water tankers.

Political Ecology and Water Justice

Political ecology is often concerned with how social power relations of formal piped infrastructure simultaneously enable and disable social and environmental conditions by improving the environmental qualities for some communities while leading to environmental deterioration for others (Swyngedouw, et al 2002; Swyngedouw, 2009). Our research contributes to the field in two ways and redirects the conversation towards informal water systems.

Political ecology looks at how water systems can produce inequitable and uneven social and ecological relations by analyzing who gains and suffers from socio-environmental changes (Swyngedouw, et al 2002; Swyngedouw, 2009). Meanwhile, the field of water justice focuses on how water struggles tend to impact lower income communities disproportionally, resulting in water disparities in access, affordability and quality (Vanderwarker, 2012; Palaniappan et al., 2006). Our case study on Beirut highlights those who gain from and pay for the informal water system and shows how informality results in an uneven access and affordability disparities. Our results of Chapter 2 show that both high and low income communities are impacted financially from the added costs of procuring water through informal water systems. However, affordability of informal sources differs across communities and leads to disproportionate water access disparities. Even though lower income residents have a lower total water cost, their residents access less affordable water, paying 2.2 times more of their income to secure water compared to high income residents. We also find that water affordability disparities are not only linked to the purchasing capacity of higher income communities, but also to their advantages in the urban structure. For example, they tend to have larger buildings, hence larger on-site storage capacities. Also, they generally have larger streets which enables larger tanker trucks to enter their neighborhood, and these larger trucks offer cheaper prices per liter of water. We also identify different coping behaviors adopted by both communities to overcome water shortages. Lower income residents change their consumption behavior by scheduling their intensive water activities (such as washing machines), while higher income communities purchase expensive water bottle brands and expensive domestic reverse osmosis units.

In addition, political ecology shows that water systems are the result of hydro-social configurations where hydrological resources are managed and controlled by social processes (Bakker, 2003; Swyngedouw, et al 2002; Swyngedouw, 2009). Scholars have analyzed these social processes by identifying the stakeholders behind water systems that are of different sectors and at multi-administrative levels (Ingold et al 2018; Mancilla Garcia et al 2019) and by unveiling their political, economic and cultural interests that impact how they manage and control access to resources (Watts, 2000; Swyngedouw, 2009). Similarly, informal water systems are also influenced by social relations, socio-cultural, and environmental drivers that indirectly influence how informal stakeholders manage and control resource. Chapter 4 advances this conversation by providing an empirical analysis of informal stakeholders' social relationship using a Social Network Analysis (SNA) approach. By developing Exponential Random Graph Models (ERGMs), we statistically identify and characterize key stakeholders controlling the informal network of water tankers and reveal the socio-cultural and environmental drivers behind Beirut's informal water system. We show that religion, years in the market, and type of exchanged information are key socio-cultural driver influencing the informal water market in Beirut. For example, we find that Muslim informal water tanker owners, are new stakeholders to the market and tend to exchange information on market prices. Moreover, we assess aspects of cooperating and competition among informal water tankers which helped reveal indirect environmental driving forces that have contributed to the emergence and development of the informal market. Our analysis shows an increase in competition in the last few years, which is linked to increase of drought events, that have increased water intermittence and expanded the use of informal water tankers, suggesting a local effect of climate change. We conclude that competition is double sided: it reduces market prices, making water more accessible to end-users; nevertheless, it can also lead to a tragedy of the commons from excessive groundwater pumping.

Hybrid Recommendations for hybrid systems

Even when informal sources are a small portion of the total water supply volume, their socio-economic and environmental impacts are still significant. For our case study, informal water sources take up to 23% of total water supply. However, 88% of total water costs are for informal sources, and households pay approximately 10 times more for informal sources than for water delivered through the public water infrastructure (Chapter 2). We also found that informal sources have very high energy use and carbon emissions (Chapter 3), being 99% of energy use and 97% of carbon emissions per cubic meter of water. They also account for 80% of total energy use and 68% of total carbon emissions per person per year. However, informal water sources are not equally harmful. Chapter 3 and 4 show that among all informal water sources, bottled water has the highest socio-economic and environmental impacts. Even though it is only 2% of total water supply, bottled water is 82% of total water costs, and 33% of total energy use and 18% of total carbon emissions per person per year. These results show that informal source are multi-faceted and complex, and that we cannot develop a one-solution-fits-all. Within informality, different sources have different scales and impacts, so different strategies are required to provide better water access.

Scholars have highlighted this complexity. Informal systems reflect an ever-shifting landscape (Roy, 2009) and are entangled with formal water systems (Bakker, 2003; Misra, 2014; Peloso and Morinville, 2014). Formal piped infrastructure provides an affordable service and informal sources provide additional volumes and quality. To transition to a more resilient and sustainable system, we need strategies that reduce socio-economic and environmental impacts of informal sources or reduce the need for them. So we suggest hybrid strategies that target different sources to improve their quantities, qualities, and costs.

A major problem driving Beirut’s water disparities and struggles is that the formal water subscription fees are a minimal share of total water cost. The very low cost of formal service affects overall revenue and budget of the water utility, greatly limiting its financial capacity to upgrade and maintain the water infrastructure system. The piped infrastructure currently has up to 45% leakage losses in its distribution systems (Shaban 2020; Bulos and Yam, 2021). This results in a vicious cycle where the piped water system's reduced fees and budget result in high supply intermittence, pushing household to rely even more on6 informal water sources. A first strategy should target upgrading of the piped infrastructure to reduce leak losses. This is currently being developed by the Lebanese water utility as an indirect method to reduce the reliance on informal tankers (Hoayek, personal communication, September 8, 2019). Another current strategy being developed by the water utility is to install household water meters which will help monitor and monetize usage, while also helping to reduce losses (EBML, 2021; Hoayek, personal communication, September 8, 2019). To upgrade the piped infrastructure, the water utility could try to increase its budget by increasing service rates. People are clearly paying added costs from other sources anyway. To estimate increased service rates, the water establishment can calculate whether the added costs that people are already paying would be sufficient to upgrade the infrastructure.

However, raising water rates would likely be politically challenging in areas that face mismanagement from governmental institutions coupled with poverty and corruption (Rogers & Hall, 2003). Public institutions are poorly managed (El Fadel et al, 2003; Alameddine et al 2018) and peoples' lack of trust in public institutions might result in unwillingness to pay more, knowing that they may not receive promised water volumes. One way to move forward is to start with a pilot project, where the water institution could gain public trust by proving that it is capable of delivering safe and reliable water quantity and quality. Other solutions could rely on multiple strategies that do not eliminate informal sources, but try to attenuate their impacts.

Economically, bottled water is currently the most expensive source. While we recognize the dangers of commodifying water (Bond, 2004), bottled water remains a necessity in areas where people do not trust the quality of tap water (Haddad, 2002; Zawahri et al., 2011; Walter et al 2017). Financial strategies and subsidies could be developed to attenuate the price of bottled water, making it more affordable for both high- and low-income communities.

From a public health perspective, strategies can focus on controlling the distribution of unregistered bottled water of dubious quality and upgrading the infrastructure to reduce or eliminate sewer pipe contamination. For example, from our survey, out of the 26 drinking bottled water brands mentioned by households, only 8 (31%) were registered by the Ministry of Public Health (MoPH, 2020). A first strategy proposes increasing water quality testing by the Ministry of Public Health to monitor the selling of unregistered and contaminated drinking water bottles and to upgrade the infrastructure to eliminate sewage seepage. However, due to poorly managed public institutions (El Fadel et al, 2003), this might not be well implemented. Other solutions propose the introduction of easy-to-use and affordable water quality testing kits to encourage residents to test their own water quality, which can be used for both bottled water and groundwater supplies. This has been adopted for communities suffering from arsenic contamination (Steinmaus et al., 2006; Kikuchi et al., 2014; Lizardi, 2017). Those kits would still need time and capital to be researched and developed. They might again result in affordability disparities, with higher income communities affording such kits, leaving lower income communities unable to test their water quality.

To reduce air pollution, one policy recommendation could be to reduce the use of old and polluting trucks with inefficient engines and push all truck owners to upgrade to more efficient engines. This could be done through management frameworks based on tariffs (Constantine et al 2017), where older trucks using old engines that pollute more, pay higher tariffs. Such strategies may formalize the informal (Ahlers et al., 2013). This might also result in a monopoly by larger water tanker companies that already control the market, as they might be the only ones able to engage and negotiate with public institutions and/or able to afford the added costs from registration fees, licenses and taxes (Ahlers et al., 2013).

Other recommendations can be designed to accommodate local customs. For example, our results show Lebanese households rely on on-site storage, with underground and roof reservoirs that require water to be pumped at a building level. This internal pumping has relatively high energy use and carbon emissions. Internal pumping is controlled by residents themselves in a decentralized way, so strategies could incentivize more efficient technologies, such as solar pumps. In Lebanon, a successful example has been the widespread adoption of solar water heaters (SWH) by households of different socio-economic levels. This was made possible through financial incentive programs that let individuals take low interest loans and subsidies to install SWH, as long as they purchase the SWH from qualified companies (LCEC, 2019). Hence, intermediate strategies could try to readapt already-in-use solutions through similar financing mechanisms and encourage individuals to use more efficient household pumps. Decentralized solutions provide flexibility in infrastructure (Brown et al. 2009; Farrelly & Brown 2014; Bichai et al. 2015) and improves community cohesion through participation that drives community involvement and empowerment (Kyessi 2005; Russell 2014).

Study Limitations

Understanding and analyzing informality is challenging because of its informal nature and its hidden characteristics (Bakker et al., 2008), which typically results in lack of data on those systems. Data availability was a main challenge for the overall analysis including 1) identifying and characterizing informal water tankers, 2) computing water affordability, and 3) computing energy-water nexus and carbon emissions of water sources.

We could not find any official or non-official list of informal water businesses. So we relied on our interview process to develop the network of informal water tankers and characterize the stakeholders. Being an informal network, we were limited to a small number of stakeholders willing to take part in interviews. Under sampling is a common problem in such research projects (Shalizi and Rinaldo, 2013), and the study sample was indeed small, which might affect our social network statistical analysis. To cope with absence of data on household expenditure, we used an income-based approach to estimate water affordability. Income values were estimated based on proxy data obtained from our own household survey answers on age, occupation, and education level, coupled with salary data from different non-governmental databases. To compute informal water costs, we also used results from our own household survey. Residents provided information on weekly or monthly purchased water including cost and volume of each informal source. Finally, to obtain energy data for informal sources, again we relied on our own household survey and our own tanker interviews.

It was not possible to triangulate our own raw data with national statistics on household water use and water tanker use since these data are not available at national level. This forced us to leverage water and energy values from case studies in other regions, which is not ideal. Future research on informal networks, should take data availability limitations into account and extend data collection periods to be able to develop larger networks and be able to gather more accurate data.

Additional challenges came from political instabilities during the data collection period, which pushed us to modify our initial random sampling methods. Households and water tankers were recruited with a convenience sampling process. This was based on interviewees’ ease of accessibility, willingness to participate, and geographic location for the households and water tankers (Etikan, 2016). We followed sample sizes used in other studies in the fields of informal water systems to meet minimum standards for valid statistical analysis given political and financial constraints (Rosenberg et al., 2007; Jepson & Vandewalle, 2016; Walter et al., 2017).

Future research directions

Future research includes three main directions: analyzing environmental and health disparities from informal water sources, exploring informality across borders by using multiple case studies, and developing a systematic framework to identify and characterize informal water systems.

While we did not measure water and air quality at any point, future research could build on our assessment to include disparities of water contamination and air pollution from informal water sources among different communities. This direction will contribute to the field of environmental justice which focuses on the disproportionate environmental burdens and exposure to toxic pollutants facing lower-income and marginalized communities (Palaniappan et al 2006).

Beirut is just one example. Additional case studies would support comparisons and contrasts with results obtained for Beirut's informal water system. We were faced with limitations on data availability on informal water sources, specifically on their costs and energy needs. Using other case studies will help develop a database for these elements, and help us triangulate these findings. Moreover, we identified Beirut's main socio-cultural and environmental drivers that indirectly influence the way stakeholders control and manage informal resources (e.g. religion, years in the market and drought events). Additional case studies will allow us to find other drivers that influence the management of other informal water sources.

Compiling multiple case studies will push breaking the north and south research divide in informality research. The literature on informal water systems covers a wide range of areas with most focusing on lower income areas. For example, most case studies look at informal water systems in south-east Asia (Misra, 2014; Ranganathan's, 2014; Kooy, 2014), Africa (Peloso and Morinville, 2014; Liddle et al., 2016), or Latin America (Marston, 2014; Wutich et al., 2016; Walnycki, 2019). However, informal systems also exist in richer countries. Some recent scholars started highlighting informality aspects in higher income areas such as California (London et al 2021; Balazs and Ray, 2014). Some exceptions have simultaneously compared higher and lower income areas, including comparing informal water systems between California and India (Ranganathan & Balazs 2015) or the borders between Mexico and USA (Jepson and Vandewalle, 2016). Using additional case studies, especially in higher income countries will show that informality occurs in multiple sites and in multiple ways.

Additionally, we could contribute to building a systematic framework to identify and characterize informal water systems. Informal systems are complex and difficult to identify because of their hidden characteristics (Bakker et al., 2008). It is challenging to evaluate them because of their ever-shifting forms, lying between legitimacy and illegitimacy, legality and illegality, authority and anarchy (Roy, 2005). They also are entangled with formal systems (Bakker, 2003; Misra, 2014; Peloso and Morinville, 2014) and vary with context and scale. Developing a systematic framework will aid in identifying and characterizing them in different contexts. The framework will include five indicators of quantity, affordability, quality, health, and environmental management. These indicators are based on methods developed in the field of water security. Water security measures whether "every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the environment is protected and enhanced" (GWP, 2000). The objective here is to understand the performance of the overall water system based on those indicators, identify its weakness and identify when informality is filling in the gaps, i.e. if the formal system is failing on water quality, then most probably an informal water system is providing a better water quality to communities, but perhaps still not the best performance.

The framework will be based on an extensive literature review including water informality case studies. The literature review will combine different methods, including scoping, and theory-building (Xiao and Watson, 2019). Our objective would be to provide a comprehensive understanding of the literature and extract data based on the above indicators from each piece of literature (Arksey and O’Malley 2005). To build our theory we will follow a meta-ethnography method “translates” and synthesize different literature studies (Noblit and Hare, 1988). This “translation” will be based on contrasting and compared case studies and on identifying their similarities and differences. The literature review will enable a systematic framework to identify and characterize informality based on the five indicators. The indicators will assess the impacts of informality, and facilitate the development of recommendations to attenuate their impacts, and action pathways to better integrate them into policies.

In sum, this research assesses qualitatively and empirically informal water systems in Beirut (Lebanon). Informal water systems are complex, they are multifaceted, and are entangled with formal piped infrastructure. They are not an option but a necessity as they help communities overcome daily water shortages. They are flexible and can adapt and compensate for the failings of formal infrastructure systems. However, they are not neutral and are influenced by socio-cultural and environmental drivers that impact the way informal stakeholder manage and control resources leading to uneven socio-environmental situations. Even when they provide a small portion of the water supply, their socio-economic and environmental impacts are still significant resulting in socio-economic and environmental disparities. A hybrid set of strategies are proposed that do not eliminate informal sources, but try to attenuate their impacts and inequalities. Finally, in water management research on informal infrastructure is still the exception. We propose elaborating this field in different ways: analyzing the correlation of health and pollution impacts of informal sources on lower income communities; exploring informality across a broader range of contexts, and developing a framework that will facilitate a systematic identification and characterization of informal systems across borders.

References

Ahlers, R., Cleaver, F., Rusca, M., & Schwartz, K. (2014). Informal space in the urban waterscape: Disaggregation and co-production of water services. *Water Alternatives*, 7(1), 1-14.

Alameddine, I., Tarhini, R., & El-Fadel, M. (2018). Household economic burden from seawater intrusion in coastal urban areas. *Water International*, *43*(2), 217–236.

Angst, M., & Fischer, M. (2020). Identifying Subsystems and Crucial Actors in Water Governance: Analysis of Bipartite Actor—Issue Networks. In *Networks in Water Governance*. (pp. 115-143). Palgrave Macmillan.

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International journal of social research methodology*, *8*(1), 19-32.

Bakker, K. J. (2003). A political ecology of water privatization. *Studies in Political economy*, 70(1), 35-58.

Bakker, K., Kooy, M., Shofiani, N. E., & Martijn, E. J. (2008). Governance failure: rethinking the institutional dimensions of urban water supply to poor households. *World Development*, 36(10), 1891-1915.

Balazs, C. L., & Ray, I. (2014). The drinking water disparities framework: on the origins and persistence of inequities in exposure. *American Journal of Public Health*, 104(4), 603-611.

Berardo, R. (2009). Processing Complexity in Networks: A Study of Informal Collaboration and its Effect on Organizational Success. *Policy Studies Journal*, *37*(3), 521–539.

Bichai, F., Ryan, H., Fitzgerald, C., Williams, K., Abdelmoteleb, A., Brotchie, R., & Komatsu, R. (2015). Understanding the role of alternative water supply in an urban water security strategy: an analytical framework for decision-making. *Urban Water Journal*, *12*(3), 175-189.

Bodin, Ö, Mancilla García, M., & Robins, G. (2020). Reconciling Conflict and Cooperation in Environmental Governance: A Social Network Perspective. *Annual Review of Environment and Resources*, *45*(1), 471–495.

Bond, P. (2004). Water commodification and decommodification narratives: pricing and policy debates from Johannesburg to Kyoto to Cancun and back. *Capitalism Nature Socialism*, *15*(1), 7-25.

Brown, R. R., Keath, N., & Wong, T. H. (2009). Urban water management in cities: historical, current and future regimes. *Water science and technology*, *59*(5), 847-855.

Bulos, N & Yam, M. (2021, April 2). Climate change and corruption endanger an ancient valley in Lebanon. *LA Times.* https://www.latimes.com/world-nation/story/2021-02-21/bisri-valley-water

Constantine, K., Massoud, M., Alameddine, I., & El-Fadel, M. (2017). The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of Environmental Management*, *188,* 85-94.

Eaux de Beyrouth et du Mont-Liban (EBML) (2021, March 01). Latest Projects. Retrieved from https://ebml.gov.lb/projects.php?lang=en

Etikan, I. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1.

Farrelly, M. A., & Brown, R. R. (2014). Making the implicit, explicit: time for renegotiating the urban water supply hydrosocial contract?. *Urban water journal*, *11*(5), 392-404.

Global Water Partnership (GWP), 2000. Integrated Water Resources Management. TAC (Technical Advisory Committee) Background Paper No. 4. GWP, Stockholm, Sweden.

Haddad, S. (2002). The relevance of political trust in postwar Lebanon. *Citizenship Studies*, 6(2), 201-218.

Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. *Renewable and Sustainable Energy Reviews*, *65*, 319–331.

Ingold, K., Driessen, P. P. J., Runhaar, H. A. C., & Widmer, A. (2018). On the Necessity of Connectivity: Linking Key Characteristics of Environmental Problems with Governance Modes. *Journal of Environmental Planning and Management*, online.

Jepson, W., & Vandewalle, E. (2016). Household water insecurity in the global north: a study of rural and periurban settlements on the Texas–Mexico Border. *The Professional Geographer*, *68*(1), 66-81.

Kikuchi, A., Mutmainah, F. N., Romaidi, S. N. H., & Soid, M. M. (2013). Applicability of Easy-to-use Escherichia coli test strip for community development program on drinking water safety. *Proceedings of the 4th Green Technology Faculty of Science and Technology Islamic of University State Maulana Malik Ibrahim Malang, Malang, Indonesia*, 183-190.

Komarulzaman, A. (2017). *Water affordability, water quality and their consequences for health and education in Indonesia* (Doctoral dissertation, Radboud Repository of the Radboud University, Nijmegen, the Netherlands).

Kooy, M. (2014). Developing Informality: The Production of Jakarta's Urban Waterscape. *Water Alternatives*, 7(1).

Kyessi, A. G. (2005). Community-based urban water management in fringe neighbourhoods: the case of Dar es Salaam, Tanzania. *Habitat International*, *29*(1), 1-25.

Lebanese Center for Energy Conservation (LCEC). (2019). *The Evolution of the Solar Water Heaters Market in Lebanon*. Ministry of Energy and Water.

Lizardi, C. L. (2017). “Penny per Test”-Low Cost Arsenic Test Kits. In *Mobilizing Chemistry Expertise To Solve Humanitarian Problems Volume 1* (pp. 51-61). American Chemical Society.

London, J. K., Fencl, A. L., Watterson, S., Choueiri, Y., Seaton, P., Jarin, J., ... & Bailey, C. (2021). Disadvantaged Unincorporated Communities and the Struggle for Water Justice in California. *Water Alternatives*, *14*(2), 520-545.

Mancilla García, M., Hileman, J., & Bodin, Ö. (2019). Collaboration and conflict in complex water governance systems across a development gradient: Addressing common challenges and solutions. *Ecology and Society*, *24*(3), art28.

Marston, A. (2014). The scale of informality: Community-run water systems in peri-urban Cochabamba, Bolivia. *Water Alternatives*, *7*(1).

Ministry of Public Health (MoPH) (2020, May 13). *List of Bottled Water Permitted by MOPH*. Retrieved from https://www.moph.gov.lb/en/Pages/4/3365/list-of-bottled-water-permitted-by-moph

Misra, K. (2014). From Formal-Informal to Emergent Formalisation: Fluidities in the Production of Urban Waterscapes. *Water Alternatives*, 7(1).

Nastiti, A., Sudradjat, A., Geerling, G. W., Smits, A. J. M., Roosmini, D., & Muntalif, B. S. (2017). The effect of physical accessibility and service level of water supply on economic accessibility: A case study of Bandung City, Indonesia. *Water International*, *42*(7), 831–851.

Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H., & Georgiadou, Y. (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, *44*, 358–366.

Noblit, G. W., Hare, R. D., & Hare, R. D. (1988). *Meta-ethnography: Synthesizing qualitative studies* (Vol. 11). sage.

Palaniappan, M., Lee, E., & Samulon, A. (2006). Environmental justice and water. *The World's Water, 2006-2007 the Biennial Report on Freshwater Resources*, 117-44.

Pattanayak, S. K., Yang, J.-C., Whittington, D., & Bal Kumar, K. C. (2005). Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal: COPING WITH UNRELIABLE PUBLIC WATER SUPPLIES. *Water Resources Research*, *41*(2).

Peloso, M., & Morinville, C. (2014). 'Chasing for Water': Everyday Practices of Water Access in Peri-Urban Ashaiman, Ghana. *Water Alternatives*, 7(1).

Ranganathan, M. (2014). 'Mafias' in the waterscape: Urban informality and everyday public authority in Bangalore. *Water Alternatives*, 7(1).

Revell, K. (2010, September). Working with informality: increasing resilience in cities of the Global South. In *46th ISOCARP Congress* (pp. 1-13).

Rogers, P., and Hall, W. (2003). Effective Water governance. In *GWP Technical Committee Background Papers No. 7*. Global Water Partnership, Stockholm.

Rosenberg, D. E., Tarawneh, T., Abdel-Khaleq, R., & Lund, J. R. (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research*, 43(7).

Roy, A. (2005). Urban Informality: Toward and Epistemology of Planning. *Journal of the American Planning Aoosication*, 71(2), 147-158.

Roy, A. (2009). Strangely familiar: Planning and the worlds of insurgence and informality. *Planning Theory*, *8*(1), 7-11.

Russell, R. (2014). Waste not, want not? Evaluating the urban sustainability implications of centralized versus decentralized wastewater treatment in Tijuana, Mexico. *Urban geography*, *35*(6), 805-821.

Sandström, A., & Rova, C. (2009). The network structure of adaptive governance-A single case study of a fish management area. *International journal of the commons*, *4*(1).

Shaban, A. (2020). *Water resources of Lebanon*. Springer International Publishing.

Shalizi, C. R., & Rinaldo, A. (2013). Consistency under sampling of exponential random graph models. *Annals of statistics*, *41*(2), 508.

Spang, E. S., Manzor, S., & Loge, F. J. (2020). The cost-effectiveness of energy savings through water conservation: a utility-scale assessment. *Environmental Research Letters*, *15*(11), 114031.

Steinmaus, C. M., George, C. M., Kalman, D. A., & Smith, A. H. (2006). Evaluation of two new arsenic field test kits capable of detecting arsenic water concentrations close to 10 μg/L. *Environmental science & technology*, *40*(10), 3362-3366.

Swyngedouw, E., Kaika, M., & Castro, E. (2002). Urban water: a political-ecology perspective. *Built environment*, 28(2), 124-137.

Teodoro, M. P. (2018). Measuring Household Affordability for Water and Sewer Utilities: Measuring Household Affordability for Water and Sewer Utilities. *Journal - American Water Works Association*, *110*(1), 13–24.

Thompson, J. et al., (2001). *Drawers of water II: 30 years of change in domestic water use & environmental health in east Africa. Summary* (Vol. 3). International Institute for Environment and Development.

Vanderwarker, A. (2012). Water and environmental justice. *A Twenty-First Century US Water Policy*, *52*.

Walnycki, A. (2019). Rights on the edge of the city: Realizing of the right to water in informal settlements in Bolivia. In *Water Politics* (pp. 99-112). Routledge.

Walter, C. T., Kooy, M., & Prabaharyaka, I. (2017). The role of bottled drinking water in achieving SDG 6.1: An analysis of affordability and equity from Jakarta, Indonesia. *Journal of Water, Sanitation and Hygiene for Development*, 7(4), 642-650.

Wutich, A., Beresford, M., & Carvajal, C. (2016). Can informal water vendors deliver on the promise of a human right to water? Results from Cochabamba, Bolivia. *World Development*, *79*, 14-24.

Watts, M. (2000). Political ecology. *A companion to economic geography*, *257*, 274.

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, *39*(1), 93-112.

Zawahri, N., Sowers, J., & Weinthal, E. (2011). The Politics of Assessment: Water and Sanitation MDGs in the Middle East: Water and Sanitation MDGs in the Middle East. *Development and Change*, *42*(5), 1153–1178.