System Archetypes Underlying Formal-Informal Urban Water Supply Dynamics

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Abstract

Contrary to developed countries, developing countries have been observed to have an increased reliance on a diversity of water supply options to meet their daily demands, where formal supply systems are incapable of fulfilling the daily needs of consumers. In filling a demand-supply gap, informal supply systems are increasingly being associated with issues of long-term sustainability, higher consumer cost, and inequity. Emerging formal-informal dynamics in developing countries require a thorough understanding of complex human-water interactions for policy direction, in order to best support the advancement of urban water sustainability. Accordingly, system archetypes offer a platform to explain the behaviors of complex systems. This paper identifies common system archetypes that define urban waterscapes in the developing world. In this way, Causal Loop Diagrams (CLDs) are used to present relationships and identify common archetypes that define the complexity of urban water supply systems in Hyderabad, Pakistan. These archetypes include 'fixes that fail', 'shifting the burden', 'limits to growth/success' and 'growth and underinvestment'. These archetypes demonstrate that increases in formal infrastructure capacity and the number of informal suppliers to increase supply reliability are symptomatic solutions, restrained by financial and technical resources, and thus have unintended consequences. Further, a number of policy instruments are discussed as leverage points to achieve financial sustainability of formal systems. This paper emphasizes the need of a policy framework for informal supply system in national and regional water policies to ensure its service reliability as a short to medium term solution.

Keywords Urban water management · Human-water interactions · Formal-informal dynamics · System archetypes

1 Introduction

Urban water supply systems have remained under pressure to meet the emerging needs of population and economic growth, exacerbated by changes related to climate (Jenerette & Larissa 2006)). Hybrid water supply systems have emerged over time to meet these grow-

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ing needs, incorporating both formal (managed by state) and informal (non-state) supply systems (Ahlers et al. 2014; Post et al. 2017). Accordingly, interactions amongst formal and informal supply systems may result in multiple configurations that can define the state of a system's reliability (its ability to deliver the demand). Understanding system structures and behaviors that define the urban waterscape are pivotal to ensuring sustainable supply. These behaviors can be understood in the light of system archetypes.

The literature on formal and informal water supply systems has mainly focused thus far on: neo-liberal inspired privatization (Bakker 2010), remunicipalisation (McDonald 2018), comparative analysis of systems' performances (Ranganathan 2014; Wutich et al. 2016), sustainability issues (Shah 2007), as well as hybrid supply patterns (Post et al. 2017). However, system level configurations of formal-informal dynamics involving coupled human-water interactions has received limited attention. Post et al. (2017) have elaborated on system level configurations of actors and roles in water provision; however, their study did not account for the dynamicity of these interactions. These interactions are continuously reshaped based on endogenous factors such as user and supplier priorities (Di Baldassarre et al. 2015) and exogenous factors such as climate change, demography and economy (Asefa et al. 2014). Sustainable urban water management requires an incorporation of these factors in planning processes (Leigh et al. 2019). This necessitates the exploration and understanding of how formal and informal systems interact to influence urban water supply reliability.

Water supply system reliability has been continuously challenged by a lack of financial sustainability within formal systems. The situation has aggravated over time as the stock of infrastructure assets reaches its designed service life, where replacement or rehabilitation has been constrained by a lack of funds (Enouy et al. 2015; Rehan et al. 2011). Developing countries are especially at the forefront of this crisis, primarily driven by water tariffs being set too low and lower tariff recovery rates. Lower performance of formal systems leads to lower consumer satisfaction and thus lower willingness to pay (WTP) to generate sufficient revenue (Grupper et al. 2021). Low WTP has further discouraged policy makers to set suitable tariff rates (Enouy et al. 2015), reinforcing the low reliability of formal systems. Informal systems, aiming to fill the demand supply gap have increasingly begun to replace formal systems (Dakyaga et al. 2021; Pattanayak et al. 2005). Whilst diversity in water supply sources may be associated with the resilience of water supply systems (Gupta 2015), informal systems have been observed to be associated with issues of long term sustainability, higher consumer cost and inequity (Kujinga et al. 2014; Majuru et al. 2016; Suwal et al. 2020).

This situation is in alignment with increasing evidence of the impacts created by traditional water management interventions, i.e., focusing mainly on short term solutions and reinforcing long-standing problem. Water supply reliability thus needs to be viewed as an outcome of co-evolving human-water interactions (Srinivasan et al. 2017). Literature on urban socio-hydrology has provided significant insights on the importance of endogenizing the human behavior in assessing water security (Li et al. 20; Srinivasan 2015). However, despite increasing efforts to understand the complexities through sophisticated modelling approaches, there is still a lack of understanding of feedback processes and interactions at the policy level, which further demotivates policy makers in applying long term solutions (Bahaddin et al. 2018).

System dynamics (SD) modelling based on the principle of systems thinking, facilitate recognition of the interlinkages that define system's behavior (Mirchi et al. 2012; Winz et

al. 2009). As an initial step in SD modelling, system archetypes provide a holistic view of system behavior, helping to understanding a system's complexities and provide a picture of the underlying structures that define a system's behavior over time (Braun 2002; Kim et al. 1998). Wolstenholme (2003) categorized system archetypes into problem and solution archetypes, where a problem archetype presents a system behavior that is different from what was originally intended. Contrastingly, a solution archetype, also referred to as leverage point tends to minimize the unintended consequences of a problem archetype.

This paper uses system archetypes as a means of identifying and examining variables and characteristics of human-water interactions in hybrid formal-informal water supply systems. This study is unique in assessing dynamicity of the formal and informal supply systems' interactions being influenced by human behavior over time through an economic lens. Whereas, previous studies have either been comparative or assessed formal and informal systems separately. Moreover, the studies on system archetypes in water resources management have majorly focused on infrastructure at basin scale (Ghashghaie et al. 2014), agriculture and environmental sectors (Bahaddin et al. 2018; Mirchi et al. 2012) and transboundary water management issues (Gohari et al. 2013; Lindqvist et al. 2021). Water supply system conditions in Hyderabad, Pakistan, effectively illustrate the situation in arid urban regions in the developing world, where the informal system is rapidly replacing the formal system in meeting consumer demand. However, lack of incorporation of informal systems in policy by city planners and policy makers raises questions regarding the future of urban water supply reliability (and its ability to meet urban demand). Diagnosing system patterns allow us to highlight and communicate possible trajectories of the system state at the strategic level and in turn to guide policy (BureŠ et al. 2016). Unlike sophisticated quantitative models, system archetypes offer a comparatively simpler way to get a holistic viewpoint through identification of problem and solution feedback loops (Bahaddin et al. 2018). The system archetypes and leverage points identified in this study will also serve as a basis for a future quantitative simulation model that will assess these interactions and account for future uncertainty.

2 Methodology

2.1 Study framework

This study adopted a qualitative SD modelling approach to assess formal-informal supply dynamics focusing on coupled human-water interactions for Hyderabad, Pakistan. The process (summarized in Table 1) involved literature review and expert consultation to identify the major factors behind low urban water supply reliability (details provided in SI Sect.1), followed by an examination of existing water management actions to determine their unintended consequences and asses possible leverage points.

The model formulation involved identification of the variables defining system's state and drawing Behavior over Time Graphs (BoTGs) to present possible patterns of variable change over time. Causal Loop Diagrams (CLDs) were drawn to illustrate the major interlinkages identified amongst the variables, defining the water supply dynamics in Hyderabad city (as mentioned in Sect.2.2). These feedback loops are comprised of reinforcing (R) and balancing (B) loops. Reinforcing loops refer to circular processes in which change in one

Table 1 Methodological framework adopted and modified from Luna-Reyes et al. (2003)

S. No	Steps in Modelling Process		Method	Details (Section)
1	Conceptualization	Problem definition	Literature review and expert consultation.	2.2
		System conceptualization	Water management techniques in the case study area are examined to determine their impact and identify the unintended consequences	
2	Formulation	Identification of variables	Key problem variables are identified that define system's state.	3.0
		Model formulation	Behavior patterns of the variables, their causal relationships, and their feedback structures are explored and interpreted	
3	Testing	Analysis of model behavior	System archetypes are identified and causal loop diagrams (CLDs) are used to interpret them	3.0
		Model evaluation	Patterns and trends examined in the CLDs are validated through findings of the prior studies including: Bano et al. 2020; Kalhoro 2017; World Bank 2014; Tahir et al. 2010; PCRWR (2021a) and Osmani & Company 2007.	
4	Implementation	Policy analysis	Leverage points/ policy actions required to overcome the challenges facing formal-informal urban water management system in Hyderabad city are highlighted and discussed.	4.0
		Model use	Future quantitative simulation work	

variable results in further change in the same direction, accumulating the component that triggered the process. Balancing loops, on the other hand, are comprised of the processes in which change in a variable is followed by a resisting or negating change, balancing the effect caused by the variable.

The behavior patterns or BoTGs are validated through comparison with findings of the prior studies mentioned in Table1 and assessed for the presence of System archetypes. System archetypes were first highlighted by Jay Forester, Dennis Meadows and Donella Meadows, later documented by Senge and colleagues in their book *The fifth discipline: The art and practice of the learning organization* (Senge 1997). The eight most common archetypes (given in SI Table2) defined by Kim et al. (1998) have been reviewed to identify patterns in the case study area.

The study concludes with discussion of existing regulatory challenges in urban water supply systems in Pakistan (in Sect.4.0), suggesting possible leverage points that could help improve the performance of the supply system. The study intends to provide a base step for future quantitative simulation work partially covered by Bano et al. (2020).

2.2 Study area

Positioned at 25° 22′ 45″ North and 68° 22′ 6″ East, Hyderabad city is situated on the left bank of the Indus River, next to the Kotri Barrage, where it acts as the last diversion structure in the Indus Basin Irrigation System (IBIS). Possessing a hot desert climate, this area receives an average annual rainfall of 127mm, usually during the monsoon period

(National Oceanic and Atmospheric Administration 2018). Surface water (the Indus River) is the only source of water supply in the city, whereas ground water is brackish and; therefore, not usable for agricultural or urban needs. Water in the city is mostly extracted from the distributary canals of the Kotri Barrage, namely from Akram Wah, Phuleli Canal and Pinyari Canal, collectively named as the Left Bank Canals (LBCs) hereafter. Some users also extract water directly from the Indus River, downstream of the Kotri Barrage (Peerzado et al. 2019).

Hyderabad is the second most populous city of Sindh, Pakistan, which has the highest population density after Karachi. The city has grown from 1.1million inhabitants in 1998 to 1.7million people in 2017 (Pakistan Bureau of Statistics 2017). Hyderabad - Water and Sanitation Authority (H-WASA) is the formal supply authority responsible for providing water in the city. The formal supply system comprises of an 1100km long supply network, with around fifty-one pumping stations, lagoons and filter plants. The city's pumping stations pump raw water from canals to the lagoons, and then on to settling tanks of filter plants through transmission mains. Hyderabad's water treatment facilities includes five filter plants (located in different sub-districts) with a total filtration capacity of 0.23million cubic meters (60million gallons) per day (Osmani & Company 2007). The present condition of Hyderabad's formal system is very poor, where the water authority merely pumps raw water from the river and delivers it to consumers. There are areas within the city that endure having no water at all in their household taps for months, whilst others may receive water for 2 to 3h per day, or on every alternate day. This situation is worse during winter, when Indus river water levels decrease (Kalhoro 2017).

Existing water management interventions have mainly been infrastructure-centric in order to augment supply. Factors affecting the formal system's sustainability, such as low revenue generation and lack of financial sustainability, have thus far received limited attention (Kalhoro 2017). A number of policies prepared over time have remained less effective due to weak implementation capacity (World Bank 2014). The situation has allowed the informal system to prevail where private individuals and companies have emerged to meet gaps. Reliance on the informal system prompts city residents of lower income groups to pay up to 20% of their monthly income to meet their domestic water demand. Further, those who can't afford this cost end up using highly contaminated water for their daily uses. As a result, water borne disease prevalence is reported to be very high in Hyderabad city. The total health cost of water pollution in the city is estimated to be 1.8% of the country's GDP (Government of Pakistan 2015).

Contrasted to this, the Hyderabad's formal system relies heavily on government funds/ tax money, where there may be a lack funds for much of the time to maintain and operate water supply systems. In this case, revenue generation is negligible due to low cost recovery (Kalhoro 2017). According to H-WASA, the recovery rate is below 50% despite having a very low tariff structure of 300 PKR (3 USD) per month, with an average supply of 6–8h per day. Low fund balance has led to poor service of the utility (Khan 2020), which in turn has led to lower satisfaction of consumers and lower willingness to pay the bills. Further to this, the situation has lead consumers to pay more and rely on alternative sources like bottled water and tankers (Zaidi 2017). Household surveys by Imad (2017) and Zaidi (2017) have revealed high dissatisfaction with water utility in Hyderabad, with an increasing proportion of informal water supply being used per household. However, despite this 40% of

households with low income have been shown to rely on poor quality water as their informal water supply.

This situation is not limited just to Hyderabad, but also exists in other major cities in Pakistan (Cooper 2018), and the developing world in general. Table SI3 summarizes statistics of water supply conditions in other major cities of Pakistan, demonstrated by coverage ratios of formal supply systems. The situation in Sindh Province is comparatively poorer, with a lack of financial sustainability, maintenance and energy deficit being constant challenges for urban water utilities, intensifying the water crisis across the whole province (Tahir et al. 2010).

3 Results

A number of systematic patterns/system archetypes are observed in Hyderabad's Water Supply System. These include:

3.1 Fixes that fail/backfire (increase in supply infrastructure and utility fund deficit):

In the case of Hyderabad city, local government approaches towards low supply reliability have mostly included an increase in the number of treatment plants, with less focus on their financial sustainability (Water and Sanitation Program (WSP) et al. 2016; World Bank 2014). Within its commitment to achieve Sustainable Development Goal (SDG) 6.1, the government of Sindh has planned to expand water supply capacity in the city by 0.38million cubic meters (100 MG) per day by 2030 (Ali 2017). Contrastingly, past development initiatives, including building of water treatment plants, have been shown to become dysfunctional after a few years due to a lack of maintenance and non-payment of electricity bills (Kalhoro 2017; World Bank 2014). Water quality assessment surveys by PCRWR (2018-19) have reported only 40% (529 out of 1300) of drinking water filter plants to be functional in 22 districts of Sindh province, whereas the number for all the districts surveyed in the country was observed to be 60% (Pakistan Council of Research in Water Resource (PCRWR) 2021b).

As presented in Fig.1a, the situation indicates the 'fixes that fail archetype', in which short term solutions i.e. increasing the number of filter plants in this case, may relieve the problem temporarily, decreasing the supply gap for a few years (B1.1). However, a lack of focus on financial sustainability has re-introduced water shortage problems again, as evidenced by the number of dysfunctional plants over time in the Sindh province (Tahir et al. 2010). New infrastructure requires the funding of maintenance and increasing overall expenditure (R1.1). Filter plants become dysfunctional once they run out of funds, where there has been a continuous increase in negative fund balances, where in turn the system's ability to sustain itself declines over time, returning water shortages to their initial conditions.

A behavior over time graph (Fig.1b) illustrates how water shortages decline temporarily every time infrastructure capacity is increased. However, this shortage returns back to its initial condition when the infrastructure degrades or becomes dysfunctional.
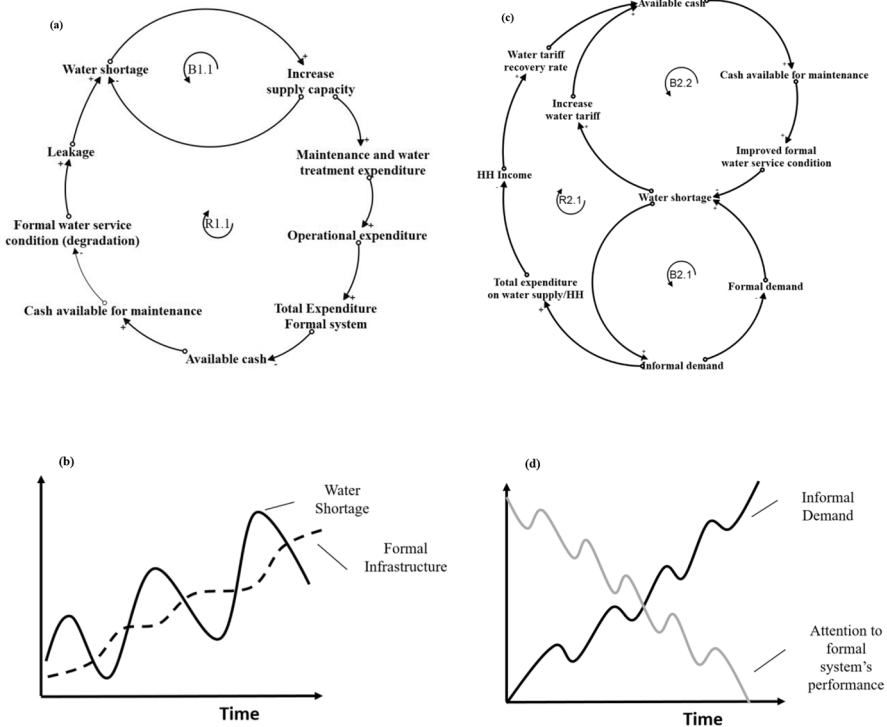
Fig. 1 (a) CLD for Fixes that fail archetype (b) BoTG for the 'water shortage' and 'formal infrastructure capacity' under fixes that fail archetype
(c) CLD for Shifting the burden archetype (d) BoTG for the 'informal demand' and 'authorities attention to formal system's performance' under shifting the burden archetype

3.2 Shifting the burden (on Informal system):

Shifting the burden archetype refers to situations in which symptomatic solutions to a problem lessen the pressure for the implementation of fundamental solutions. Whilst a symptomatic solution temporarily reduces the intensity of a problem, these symptoms can/often resurface over time (Kim et al. 1998). Informal supply has been introduced as a symptomatic solution to water shortage in Hyderabad city, and in other cities in Pakistan (Hassan 2018). Informal supply appears to fill the gap and temporarily, solving issues related to the formal system, as illustrated in B2.1 (in Fig.1c); however, water shortages and quality issues in cities have resurfaced related to an ever increasing demand for informal supply. Given this situation in most urban areas within the country, the federal government of Pakistan has allowed private suppliers to grow, which has temporarily relieved the situation. However, side effects that the informal system creates have aggravated the main problem, leading to low reliability, high cost to consumers and inaccessibility for lower income groups (Hassan 2018; World Bank 2014). As shown in R2.1, the higher expenditure associated with informal water demand at the household level reduces the ability of lower and medium income groups to pay water tariffs within the formal system (Bano et al. 2020). While tariff rates in

city areas are already low, lower recovery rates have discouraged policy initiatives to revise tariffs for the system to generate sufficient revenue (Bano et al. 2020; Imad 2017). Thus, efforts to improve the financial sustainability of the formal system, including tariff increases (B2.2), have received less attention, intensifying the need for growth of informal systems (as illustrated in Fig.1d). This further raises questions regarding whether or not the informal system is capable of meeting increasing demand in the long run. The next archetype, in Sect.3.3, discusses this further.

3.3 Limits to growth/success (Informal supply):

Limits to growth/success archetypes present scenarios where actions initially result in growth/success, which further encourages the same actions. However, over time, as growth continues, a balancing loop driven by resource constraints slows this progress. This can then mislead to further pushes of actions in the same direction (Kim et al. 1998) .

Increasing informal demand associated with water shortage in cities has increased informal supply, as shown in Fig.2a (R3.1). The number of tanker water suppliers and private companies selling bottled water has increased dramatically over the years (Pakistan council of Research in Water Resource (PCRWR) 2021a). However, this increasing demand pressure has also been observed to be associated with decreasing quality of informal supply service (B3.2). PCRWR has shown that the number of private companies selling low quality bottled drinking water has increased over time (Pakistan council of Research in Water Resource (PCRWR) 2021a) (SI Fig.1). This may be driven by financial and infrastructural constraints for informal supply systems, resulting in a compromise in quality (Dakyaga et al. 2021).

Moreover, further feedback that may affect the growth of reliable informal systems relates to a decline in the purchasing power of consumers, coupled with increase in informal demand share in total household demand. This, in turn, can increase household total expenditure, especially impacting lower and middle-income categories, whilst limiting their informal demand over time (B3.1) as they may opt for low quality free supply (Bano et al. 2020). These factors can, therefore, affect the growth of the informal system in the long run (Fig.2b). This scenario indicates 'limits to growth/success behavior' of informal systems, suggesting the need to assess the reliability of informal supply systems as a sustainable supply option.

3.4 Growth and underinvestment (Infrastructure maintenance)

The 'growth and underinvestment archetype' refers to a situation in which growth approaches a limit that could otherwise be extended or avoided via a capacity increase, resulting in further limitations of growth due to delays within a system (Kim et al. 1998). Similarly, as illustrated in Fig.2c, formal infrastructure ageing and its resulting decline in water supply due to leakage losses, can be majorly associated with increasing water shortages in Hyderabad city (Kalhoro 2017). Due to a lack of funding resources and related delays, authorities have provided less attention to infrastructure rehabilitation, which has resulted in the failure of water supply systems after a few years (B4.1). Increasing urban water demand related to population and economic growth and resulting water shortages have resulted in an increase in shifts towards informal supply systems. This demand shift and resulting decline in formal
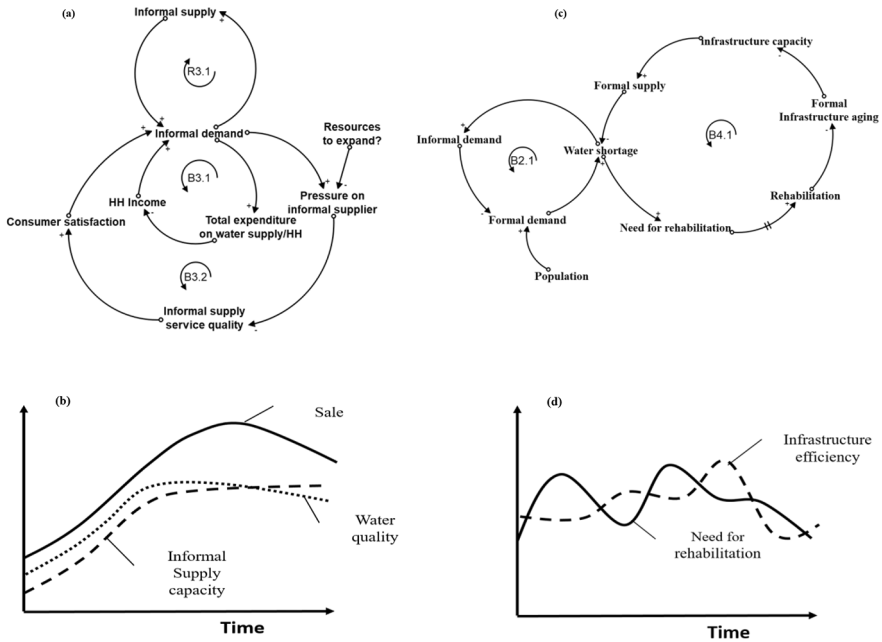
Fig. 2 (a) CLD for Limits to growth/success archetype (b) BoTG for 'informal supply capacity' and 'informal system's performance' under limits to growth archetype
(c) CLD for Growth and underinvestment archetype (d) BoTG for the 'formal infrastructure's performance' and 'need for rehabilitation' in Growth and underinvestment archetype.

demand may be misperceived as lowered demand (B2.1). This in turn, may further misguide the need for infrastructure rehabilitation. Feedback loop B4.1 may appear to be in conflict with B1.1; however, the latter refers to new infrastructure rather than to rehabilitation of existing infrastructure.

Figure2d presents how lack of infrastructure rehabilitation may ultimately lead to the infrastructure dysfunctionality after some period of time.

4 Discussion

4.1 What leverage points can help mitigate the problematic feedbacks loops in hybrid water supply systems?

Leverage points for the existing situation of urban water supply under formal-informal dynamics are identified following guidelines defined by Meadows (1997). Leverage points refer to the places in complex systems where a small change in one element can lead to a big change in the whole system. Our review of the existing literature suggests that, management of 'fixes that fail' and 'growth and underinvestment' archetypes lie in improving the existing condition of formal systems, emphasizing on its financial sustainability. Contrastingly,

the archetypes of 'shifting the burden' and 'limits to growth' can be managed by improving informal services' capacity and service regulation.

Management of 'fixes that fail' (Fig.1a-b) requires understanding of root causes, and how they are different from symptoms. Instead of focusing only on building new infrastructure every time, i.e., water treatment plants, authorities need to focus on building the financial capacities of existing formal supply systems, i.e., water utilities. Efforts are needed to: generate enough revenue through appropriate pricing mechanisms, prompt improvement in recovery rates, allocate sufficient development funds, and introduce other interventions necessary to ensure the financial sustainability of the formal system (Shin et al. 2021). Moreover, management of the 'growth and underinvestment archetype' (Fig.2c-d) requires further understanding of capacity needs with growth and avoiding perception and capacity acquisition delays that can backlog system performance (Kim et al. 1998). This may appear as contradictory to the management of 'fixes that fail' archetype mentioned above; however, management of 'growth and underinvestment' refers to rehabilitation of existing infrastructure instead of introducing new infrastructure.

In general, a water utility's financial capacity defines its service quality. In this regard, the lack of enough funds for maintenance expenditure has been observed to be associated with an increased number of dysfunctional treatments plants (Tahir et al. 2010). Urban water utilities in Pakistan rely on a combination of development funds from the federal government, external funds from international organizations and revenue generated by water tariff collection. Pakistan's water tariff has been too low, where its combination with low recovery rates has led to low revenue and higher financial deficit. Although, Pakistan's National Water Policy (NWP) 2018 outlines revised water pricing as a means of enhanced water use efficiency (Government of Pakistan 2018), according to Arfan et al. (2020), this policy lacks a clear direction regarding valuation methods for larger consumers including agricultural and industrial entities. However, the Sindh government's latest initiative of pricing industrial water (Tunio 2020) could be helpful in regulating larger water consumers.

As the debate on water pricing mechanisms continues both in favor of volumetric pricing and flat rates based on their suitability and efficiency (Hoque et al. 2013), the challenges of high transaction costs and corruption at root levels highlighted by Shah (2007) still hold true for Pakistan, that further discourage the demand management strategies. Public Private Partnership (PPP) has been gaining interest as one potential way to improve tariff recovery rates (Government of Pakistan 2002). In Hyderabad, WASA's tariff recovery rates have been reported to have improved from 50 to 70% in 2019 through public private partnership (Ahmad et al. 2019). Conversely, high shares of total revenue from private sectors may still conflict with the objective of financial sustainability (Shah 2007). However, PPP may still be effective in terms of furthering experience and knowledge in managing formal system/ utilities through management contracts (Ahmad et al. 2019; World Bank 2014).

Moreover, ensuring consumers' satisfaction with the service quality would need to be guaranteed to improve consumer's WTP. Bano et al. (2020) observed that a monthly tariff of USD $12 (an amount that city residents have shown a willingness to pay) with recovery rates of 50% and 80% could generate enough revenue to cover the operational and maintenance expenditure of Hyderabad's WASA. However, due to poor service quality and reliance on informal system, consumers' actual expenditure far exceeds the amount they are willing to pay.

An effective combination of demand management approaches would be needed, including smart meters, to prevent corruption and incorrect record of consumption and prices. Further, new approaches would need to gauge the amount consumers would be willing to pay, conditioned to improvements in water supply within the formal system (Imad 2017). Technological interventions via renewables including solar and wind energy, which might reduce formal system expenditure on energy, might also be effective for a city like Hyderabad, with greater potential for both these sources. Further to this, careful analysis of the feasibility of technological solutions would be needed, as past interventions like Reverse Osmosis plants in Tharparkar, Sindh have not been sustainable, given the lack of financial and human resources to maintain this expensive technology (Ebrahim 2015).

In dealing with 'shifting the burden' archetype (Fig.1c-d), it is necessary to consider how the coexistence of formal and informal systems would likely affect the reliability of water supply. Currently, it would be impossible to reverse the increasing reliance on informal supply, as it is considered to be the safest and most reliable source, especially for domestic use (Walter et al. 2017). Thus, it is necessary to consider means of keeping the informal system sustainable in meeting both the short and medium-term needs. Given the increasing issues associated with the reliability of informal systems, efforts are also needed to regulate the system. In Pakistan, PCRWR has been assigned responsibility for monitoring the quality of informal supply, i.e. bottled water, where it publishes quarterly water quality reports for each district (Pakistan Council of Research in Water Resources (PCRWR) 2020). However, monitoring is limited to bottled water but not tanker supply.

Management of the 'limits to growth/success archetype' (Fig.2a-b) requires researchers to ponder over the factors that may limit the growth of the informal system as a reliable source in terms of access and quality of service. Given the increasing number of people and companies entering the water supply business as a source of earning, it is pertinent that the local authorities take necessary steps to keep informal suppliers informed. These steps could include, guidelines on installation, operation and maintenance of the informal systems along with the monitoring mechanisms to ensure their effective implementation. Pakistan's National Water Policy 2018 does not recognize the role of informal systems in meeting daily water demand. Although the Sindh Drinking Water Policy 2017 suggests promotion of informal water supply through private provision, PPP, NGOs and community organization, a policy framework has yet to be released (Government of Sindh 2017).

5 Conclusion

This study uses system archetypes to identify problematic human-water interactions in hybrid urban water supply systems and the unintended consequences of water management interventions. Summarized in Table 2, the archetypes 'fixes that fail' and 'shifting the burden' illustrate how the water supply system in Hyderabad, and in other cities in Pakistan, has evolved with symptomatic solutions, thereby lacking long-term and sustainable solutions to ensure the financial sustainability of the formal system. The 'limits to growth' archetype presents that whilst the informal supply system is increasingly gaining the major proportion of water supply responsibility, it may be limited by its inability to grow due to financial and infrastructural limitations. The 'growth and underinvestment' archetype presents how the formal system has lacked the ability to meet growing needs due to underinvestment in

Table 2 Summary of system archetypes and leverage points for Hyderabad water supply system

System Archetype	Figure	Structural Hypothesis	Parameters assessed	Sources of validation	Leverage Points
Fixes that fail/ backfire	1a, b	Expansion of formal supply system i.e. addition of new water supply infrastructure reduces the water shortages in the short run. However, water shortage conditions keep recurring as the fund deficits increase over time.	(1) Total formal water supply capacity, (2) Household water balance	(Water and Sanitation Program (WSP) et al. 2016) (World Bank 2014) (Tahir et al. 2010)	Addition of new infrastructure will not suffice until formal system's financial sustainability is not ensured through restructuring existing water tariffs and increasing the development fund allocations by the government.
Shifting the burden	1c, d	Promoting the informal supply system gives a false impression of reduction in water demand to formal authorities. This further discourages the interventions needed to improve the formal system.	(1) Formal-Informal supply ratio per HH (2) formal water tariff recovery rate (3) Household expenditure on informal water supply	(Bano et al. 2020)	While regularization mechanism exists for bottled water, tanker suppliers are also needed to be monitored. Local authorities need to keep informal suppliers informed providing guidelines on installation, operation and maintenance of the infrastructure.
Limits to growth/success	2a, b	Increase in informal demand will lead to growth in informal suppliers however limited financial and infrastructure resources will constrain them to upscale resulting in low quality supply by the informal suppliers to meet the increasing demand.	(1) Informal supply capacity (2) Quality of informal supply over time	(Pakistan Council of Research in Water Resource (PCRWR) 2021b)	National Water Policy (2018) needs to recognize the role of informal suppliers, devising a policy framework to promote informal suppliers for the short and medium term needs.
Growth and underinvestment	2c, d	Ageing formal infrastructure requires regular maintenance and rehabilitation to keep the supply system functioning. Underinvestment in maintenance/ rehabilitation against the increasing water demand leads to infrastructure dysfunctionality.	(1) Formal systems fund balance (2) Number of dysfunctional water treatment plants	(Osmani & Company 2007) (Wolstenholme 2004) (Kalhoro 2017) (Tahir et al. 2010)	Policy efforts are needed to improve the tariff structure and recovery rates so that enough revenue could be generated locally to cover the operation and maintenance cost.

infrastructure maintenance. Further, this study argues that lack of incorporation of informal systems in policy raises questions regarding the future of urban water supply reliability. Identifying system archetypes allow us to highlight and communicate possible system trajectories at the strategic level and in turn to guide policy. Unlike sophisticated quantitative models, system archetypes offer a comparatively simpler way to get a holistic viewpoint

through identification of problem and solution feedback loops. Although, being generic in nature, system archetypes may rarely be sufficient in themselves, but they offer a foundation for a model to be constructed that can be helpful in simulating a system's behavior in the long run. System archetypes may often be identified to oversimplify a problem, erasing the uniqueness of a situation, whereby the generalizable relationships identified in this study are based on the data available for urban areas in Pakistan. The findings of this study will serve as a basis of a future quantitative simulation model that will assess these interactions under future uncertainty.

Supplementary Information The manuscript contains supplementary information available at https://ro.ecu.edu.au/.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for publication Not applicable.

Conflict of interest Authors declare no conflict of interest.

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