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SUSTAINABLE URBAN WATER SUPPLY: A SYSTEM DYNAMICS APPROACH

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Abstract
Water scarcity is an escalating global concern, driven by rapid urbanization, industrial growth, population increase, and climate change. These pressures have led to significant depletion of groundwater resources, particularly in developing countries where approximately 80% of potable water is sourced from underground aquifers. In Pakistan, freshwater infrastructure is often developed in an ad hoc manner, responding to immediate service deficiencies such as low pressure, inadequate quantity, and poor quality at the consumer level. This reactive approach places unsustainable stress on groundwater reserves and results in inefficient financial resource allocation. Despite the urgency, Pakistan lacks a structured framework to guide the planning and development of freshwater supply systems. This study introduces a conceptual systems framework utilizing Causal Loop Diagrams (CLDs) to model the dynamic interdependencies among hydrological, infrastructural, socio-economic, and policy-related factors within urban water supply systems. The framework is intended to support strategic decision making and promote sustainable urban water management. Preliminary validation through expert consultation and scenario analysis highlights its potential to inform resilient infrastructure planning

INTRODUCTION

Water is not only vital for domestic consumption but also plays a pivotal role in the socio-economic development of nations. It is integral to daily household activities, agriculture, and industry sectors (Alcamo et al., 1997). Naturally available potable water is scarce, founding only about 3% of the global water supply, of which approximately 2% is comprised of glaciers and polar ice caps, leaving just 1% as accessible freshwater (Abedin & Rakib, 2013). Freshwater resources worldwide are suffering with rapid depletion, a challenge exacerbated by accelerated population growth, particularly in developing nations. Presently, 30 countries are classified as water-stressed, with 20 of these experiencing absolute water scarcity. This number is projected to rise to 35 by 2020 (Vairavamoorthy et al., 2007). As, over the next 50 to 75 years the global population is expected to grow by over three billion, more than doubling the urban population (Jury & Vaux, 2005). One of the most significant impacts to the availability of freshwater is climate change, which disrupts hydrological cycles through rising temperatures, altered precipitation patterns, and seasonal unpredictability. These changes influence water demand, typically increasing consumption during dry and warm seasons while reducing it during cooler, wetter periods, thereby impacting municipalities' capacity to meet present and future water demands. Such scenarios may demand the development of new water sources, with evaluations incorporating climate change projections (Palmer & Hahn, 2002). In arid and semi-arid regions, rainfall is the prime source of recharge for both surface and groundwater resources; however, it is often sparse and highly variable in spatial and temporal distribution (Murad et al., 2007). In developing countries, the availability of fresh water is found to be critically short constrained by high population growth rates and widespread poverty. At present, approximately one billion people lack access to safe and affordable drinking water, and twice as many lack adequate sanitation services. Water distribution networks in these areas are typically designed for continuous supply but are operated intermittently, resulting in volumes lower than consumer demand (Batish, 2003). The developing countries abide either inadequate water quantity or other difficulties such as power cuts etc. and it is important to consider these realities while designing and operating such water distribution networks (Kalanithy Vairavamoorthy et al., 2004). Globally, water consumption is increasing by approximately 1% annually. Without effective policy interventions, it is estimated that only 60% of the required water will be available to the global population by 2030. The identification of Comprehensive problem is crucial for addressing complex water management challenges; overlooking to assess underlying causes often results in ineffective policies that fail to resolve issues and may create additional resource pressures (Keyhanpour et al., 2021). Pakistan, a developing illustrates this crisis, transitioning from a freshwater-abundant to a water-stressed nation within recent decades. Per capita freshwater availability declined from 2,172 m^3 in 1990 to 1,306 m^3 in 2015, with 74.3% of supply extracted from underground aquifers. The country crossed the 'water stress' threshold in 1990 and the 'water scarcity' threshold in 2005, with projections signifying it will become one of the most water-stressed nations in the region by 2040, ranking 27th globally (UNDP, 2014).

Sustainable freshwater consumption and environmental protection require minimizing water losses within distribution systems, a critical factor in improving supply efficiency (L. S. Araujo et al., 2006, Ahopelto & Vahala, 2020). Water access at the household level is also influenced by demographic variables (age, gender, education of the household head), economic status (monthly income), travel time to the source, and household size (Kithinji, 2015). Water distribution pipelines, as buried infrastructure, are subject to deterioration not exclusively determined by age, but by factors including material composition, temperature drifts, and external loading upon it (American Water Works Service Co., 2002). Material properties, environmental conditions, and operational loadings contributing to system failures (Rezaei et al., 2015). The driving need for rehabilitation and replacement cause due to failures. The rehabilitation methods include non-structural linings (cement mortar, epoxy) and structural linings (slip lining, cured-in-place pipe, fold-and-form, close-fit pipe), while replacement may include trenchless methods (pipe bursting, micro-tunnelling, horizontal drilling) or traditional open-trench excavation (Selvakumar et al., 2002).

The complexity of freshwater management poses challenges for developing predictive system dynamics models, particularly under conditions where groundwater recharge is absent and depletion is imminent. A systems approach enables interacting stakeholders to understand the interactive impacts of various factors, supporting informed decision-making for seeking alternatives (Qin et al., 2012). As early as the 16th century, scholars from Thomas More to Pogo observed that well-intentioned solutions often produce counterintuitive effects. Forrester

(1971) defined this as the "Counterintuitive Behaviour of Social Systems," wherein interventions can generate unintended consequences that complicate system management (John D. Sterman, 2000). System dynamics, pioneered by Forrester in the 1960s and popularized through the Limits to Growth study by the Club of Rome in the 1970s, models complex systems via feedback loops over time. The approach has since been applied in sectors including urban transport, economics, natural resource management, and public health (W. C. De Araujo et al., 2019). Effective water management requires vigorous modelling tools supporting boundary setting, impact assessment, and integration of data (Zare et al., 2019). In Canada, system dynamics approach has been employed to assess the long-term financial sustainability of water utilities (Rehan et al., 2011) and to parameterize models over century-long planning prospects for wastewater systems (Rehan et al., 2014). Similar approaches have informed both short and long-term operational and policy recommendations for urban water distribution (Rehan et al., 2013), discovered demand management trials, tested scarcity-responsive tariffs, evaluated wastewater reuse, and examined inter-basin transfers (Araujo et al., 2019). Current work has confirmed the value of system dynamics for balancing water supply and demand, identifying sustainable planning horizons, and optimizing surface and groundwater utilization (Xu et al., 2020; Naeem et al., 2023).

The development of sustainable urban water infrastructure requires understanding of complex interactions between physical systems, environmental conditions, social dynamics, and financial restraints. In Pakistan, the traditional approach of extending service coverage via installing new tubewell based systems, focusing to meet unmet demand lacking of addressing systemic inefficiencies. Such systems are inherently socio-technical, with interconnected feedback loops across technical, financial, and social dimensions. At present, there is no holistic planning framework in many developing countries that integrates the dynamic and complex characteristics of water supply systems throughout their planning, design, execution, operation, and maintenance stages.

Modelling Complexity of Urban Water System:

The structure and operation of urban water systems are inherently complex interacting system, involving multiple interdependent sectors (Grigg and Bryson, 1975) identified four key interconnected sectors: population, water use, water balance, and financial accounting—within a simulation modelling framework. Building on this footing, (Kotz and Hiessl, 2005) applied an agent-based modelling approach in order to simulate technical novelties and capture dynamic interconnections within these systems. (Guest et al., 2010) used a qualitative system dynamics approach to map interconnections among sustainability extents in decentralized wastewater systems. Similarly, (Ahmad and Prashar, 2010) modelled the interactions among freshwater availability, water demand, land use change, and population growth using system dynamics. (Adeniran and Bamiro, 2010) examined operational, financial, distributional, and production components of municipal water supply systems, exclusive of physical sectors: water and wastewater infrastructure. (Cheng and Chang, 2011), integrated socio-economic, demand forecasting, and population dynamics sub-models to forecast urban water supply demand, incorporating differences in mean income and unemployment rates.

In Pakistan a developing country, the urban water supply system can be conceptualized as comprising three principal sectors: social, financial, and physical/technical (Figure 1). The social sector includes population size, growth rate, density, customer satisfaction, affordability, and political influence. While, the political oversight can enhance accountability, excessive interference often impedes the establishment and expansion of new water supply facilities. The financial sector encompasses capital investment requirements for system development, operation, and maintenance, along with revenue generation and external grants. The physical/technical sector includes patterns of urbanization, hydrological cycle variability, availability of freshwater resources, the configuration of the water distribution network, interactions with existing infrastructure, and physical water losses. Sustainable urban water management requires a decision-making framework that explicitly addresses the interconnections among social, financial, and physical/technical sectors. Considering these interactions is essential for developing resilient, efficient, and equitable water supply systems in resource-constrained settings. The details of the sub-sectors considered in this study and its behavior within the complex urban water supply system are illustrated as under:

Social Sector:

Social sector is related to human beings and the sub-sectors: population, population density, population growth rate, pumping hours and average daily demand are considered while the other sub-sectors are often overlooked. For achieving social sustainability social sub-sectors need to be considered in the decision making (Brown, 2008). Using the social sector accompanied with sub-sectors are common in the developing countries only in the execution and operations, completely unaligned to the definition of these in the projects of developed world countries (Mihelcic et al., 2009). The social sub-sectors except pumping hours causes change in the same direction leading to an increase in demands for provision of physical urban water supply infrastructural components, its operation and maintenance accompanied with increase in funds allocation.

Financial Sector:

The capital, operational, maintenance and salvage value cost are the typical and easiest way to qualitatively and quantitatively measures the standards of a project. Where, the life cycle costing provides a tool for developing understanding of the decision makers upon cost comparisons evaluating alternatives via analyzing cost drivers and identifying cost adjustments of project life cycle (Rebitzer et al., 2003). For rehabilitation or upgradation of infrastructure, the comparison of among alternatives on the basis of incremental costs is recommended, against the average costs (Daigger, 2009). Incremental costs is the difference between the mostly likely to considered alternative, and the cost avoided upon its selection. The financial sector having sub-sectors: tubewell construction cost, tubewell operating cost, available funds for provision new tubewells, funds available for network construction, per kilometer network construction cost, salvage value of network, annual network maintenance and the total funds available for developing, operating and maintaining the entire urban water supply system. All the subsectors mentioned causes change in the same direction leading to an increase in the total fund's allocation The increase in funds allocation will provides opportunities to meets the demands for provision of physical urban water supply infrastructural components, its operation and maintenance.

Physical/Technical Sector:

Efficient and well-maintained physical/technical sector serves as important component, playing a vital role in enhancing the serviceable life of the entire urban water supply system. The physical/technical sector is related to the infrastructural components of the urban water supply and their condition the sub sectors involve are: installed tubewells, average tube well yield, network length installed, network condition, serviceable life, leakage fraction and leakage losses. All sub-sectors except installed tubewells and network length installed causes change in the same direction leading to an increase in demands for provision of physical urban water supply infrastructural components, its operation and maintenance accompanied with increase in funds allocation. The understanding of developing correlation among the existing water supply network and its condition viewing its deterioration throughout its serviceable life is very important. The deterioration of water supply network depends upon several factors allowing several deterioration functions to be implemented for understanding its deterioration from state of condition to another (Younis and Knight, 2010 a, b,), (Tabesh et al., 2009) and

(Savic et al., 2006). The condition of network qualitatively and quantitatively measures via assessing failure rates for pipe seeking variables i-e pipe diameter, length, pipe installation depth, average prevailing hydraulic pressure (Shirzad & Safari, 2019). The expectancy of serviceable life of pipes in the developing countries is very difficult with minimal literature support. However, the developed world for example Canadian government indicated the expected service life for different civil infrastructure assets (Ministry of the Environment Ontario, 2007). But the flexible systems dynamics approach allowed the deployment of the model setting for any value, of average serviceable life of pipe.

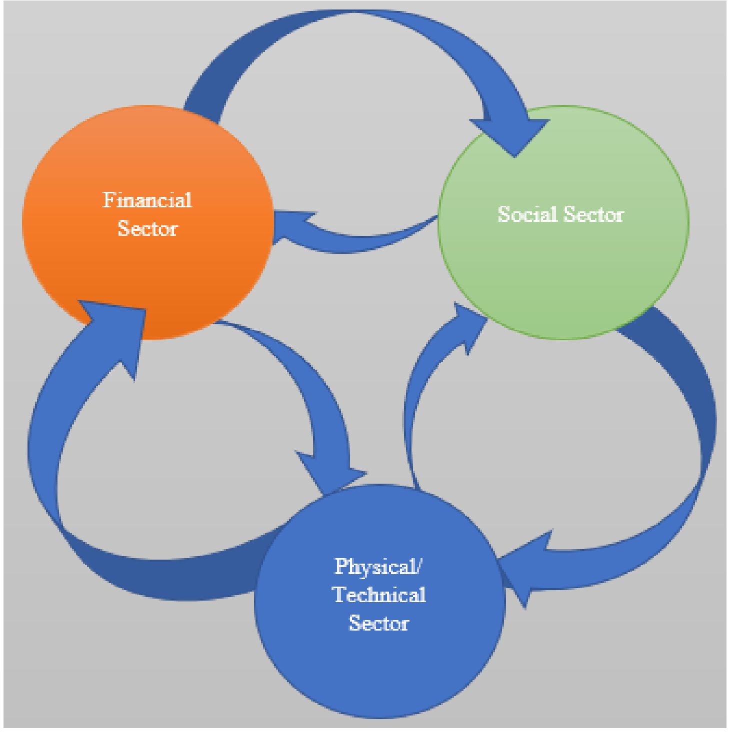

Figure 1: Interacting Sectors of Sustainable Urban Water System.

All these sector and sub sectors contributes to the urban water supply system leading the system towards more complex and dynamic nature. The interaction of sectors and sub sectors leads to complex behavior in the form of feedback loops. Upon change of a sector within a feedback loop, the stimulation originates within the feedback loop changes the originating sector. A loop is termed as a self-reinforcing loop or positive loop, if the change in the originating sector causes changes in the interacting sectors resulting strengthening the original process. In negation, if the other sectors in the feedback loop oppose the original process, then the feedback loop is termed as a balancing loop or negative loop (Hannon and Ruth, 1994). As the causal loop diagram consider to very important to understand the complexity and dynamic nature of a system. The causal loop diagram (CLD) for any complex system represents the relationship between the interacting variables to qualitatively represents the relationship through their proposed increase and decrease. The casual loop diagram comprising of casual link having an arrow pointing a dependent variable through arrow head with independent variable towards its tail. While the propose/expected increase and decrease can be represented through polarity plus (+ sign) for increase in dependent variable due to increase in independent variable and polarity minus (- sign) for decrease in dependent variable due to increase in independent variable respectively. The interaction of variable through these causal links leads to the development of casual loops (Sterman, 2000). Feedback loops comprising of various sectors related to urban water supply system are represented in Figure 2. Wherein, the reinforcing and balancing loops are presented in bold font accompanied with bold curved arrows around the respective loop names depicting the direction of its impact whether balancing or reinforcing.

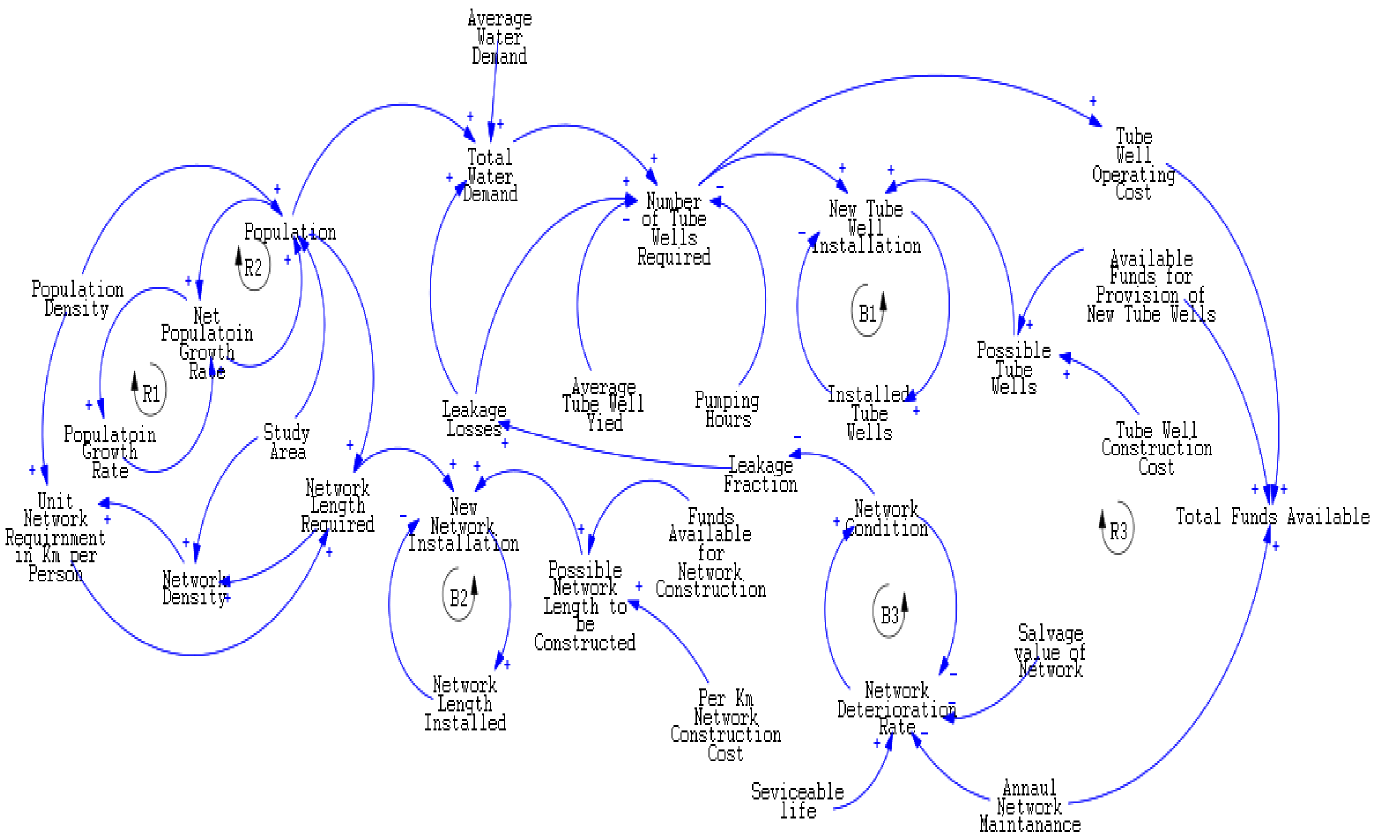

Figure 2: Casual Loop Diagram for Sustainable Urban Water System.

Feedback loop (R1 & R2) in population, net population growth rate and population growth rate:

Reinforcing loops R1 & R2 shows the typical increase in population with time based upon the increase in growth rate and net growth rate. The feedback loop R1 illustrates the Net population growth rate is a function of population growth rate showing direct relation while R2 represents accumulation of population as function of net population growth rate over time.

Feedback loop (B1) in New Tubewell Installation and Installed Tubewells:

The requirement of new tubewells will be counter back by a balancing loop between new tube installation and installed tubewells. The new tubewell installation is in direct correlation with the number of tubewells required viewing the possibility of tube wells to be installed subject to the availability of fund. The feedback loop (B1) illustrates the decrease in tubewell installation and accumulation of installed tubewells over time.

Feedback loop (B2) in New Network Installation and Network length Installed:

Requirement of constructing new network installation will be counter back by a balancing loop between new network installation and network length installed. The new network installation is in direct correlation with the network length required viewing the possibility of network to be installed subject to the availability of fund. The feedback loop (B2) demonstrates the decrease in tubewell installation and accumulation of installed tubewells over time.

Feedback loop (B3) in Network Condition and Network Deterioration Rate:

There a novel contribution of this study is to develop relationship of the network condition with network deterioration rate in terms of depreciation over time. As in Fig. 1 a holistic approach of incorporating all the components involves in the urban water system is presented form the pumping of water to the distribution work seeking the availability of funds for maintenance, operation and installing new tubewell or required length of network to be installed. The feedback loop B3 demonstrates rate of deterioration in terms of currency/depreciation and condition of network in percentage of the depreciation of the capital cost of the installed network over time.

Feedback loop (R3) among Annual Network Maintenance, Available funds for Provision of New Tubewells, Tube Operating Cost and Total Funds Available:

Reinforcing feedback loop (R3) represents the overall operation of the urban water supply system wherein, the availability of funds for network maintenance, provision of new tube wells, operating cost of tube well increase the demand of funds and in true spirit question the serviceable life expectancy of the system. Deficiency in funds availability will increase the rate of deterioration degrading network condition mitigating the sustainability of the urban water systems.

Discussion:

The causal loop diagram (CLD), presented in the previous section is first known CLD for management of urban water supply system in the developing countries. Focus on visions and missions by individual water departments or organizations leading initiation of problems i-e duplication of efforts, efficiency loss and exertion in performance improvement (Dell, 2005). The use of CLD can enlightened the interacting sub-sectors of various associated water departments or organizations discouraging their individual working culture. CLD, overcomes "Silo" approach visualizing the interconnections across the departmental or organizational boundaries avoiding exploitation of available resources (Wolstenholme, 1999). This approach is important if consequences of an action in organization felt in the other. CLD, leads understanding of complex challenges faced by a water department or organization accompanied, with the development of shared farmwork to cope with those challenges. Therefore, although CLD show causal relationships in a qualitative way only, this feature is valuable in its own right. The impact of the interacting sectors and sub-sectors can be qualitatively through formal mathematical models i-e Multi-Attribute Utility (MAU), Out Ranking Approaches and Analytic Hierarchy Process (AHP) (Belton & Stewart, 2002). The presented CLD identifies several interacting feedbacks loops demonstrating the complexity of planning, developing, operating and maintaining the urban water supply system in developing countries.

Conclusions:

The causal loop diagram (CLD), presented in the previous section is first known serve as a novel paradigm for providing a holistic analysis framework for planning, designing, execution, operation and maintenance of the urban water supply system in Pakistan.

An extreme complex situation notices while understanding impacts arises due to individual and dynamic nature and their interaction. This research promotes the use of system dynamics for the planning and management of sustainable urban water supply systems in developing countries along with the efficient and serviceable operation of the existing ones. Analyzes the interactions of impacts rising from different stakeholders of the ecosystem.

The interconnections presented in CLD are based upon the understanding of developed system dynamic model from literature review, bridging research collaboration with the professionals and extensive interactions with the operators of local utility. The presented CLD can be improved: advancing state of knowledge through critiqued.

The important contribution of the CLD, is to established the existence and development of interconnecting feedback loops. Demonstrating the inadequacy of existing traditional management techniques involves in urban supply systems. Identify stimulation in an individual component of system and its reverberation within the entire system.

CLD, will also be helpful to seek out alternatives, considered as a shift towards or away from a sustainable urban water supply system.

CLD, serves as a basic skeleton for developing mathematical models resulting policy recommendations for sustainable urban water supply systems.

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