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Equitable Urban and Rural Water Supply in Developing Countries under Intermittent and Continuous Systems

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ABSTRACT

Ensuring equitable water supply in developing countries remains a persistent challenge, particularly where intermittent water supply (IWS) prevails. This review synthesizes findings from diverse studies on IWS and continuous water supply (CWS) systems in rural and urban contexts, focusing on India, sub-Saharan Africa, the Middle East, and elsewhere. It outlines how rapidly growing populations, insufficient investment, and limited governance capacity often drive utilities to adopt IWS for rationing scarce resources. Frequent pressurization cycles in IWS exacerbate leakage, induce contamination risks, and disproportionately disadvantage poorer households, who often lack the storage facilities and resources available to wealthier ones. In contrast, CWS approaches—common in higher-income regions—maintain reliable pressure and safeguard water quality but demand substantial capital expenditures to manage leaks and upgrade aging infrastructure. Case examples underscore that successful transitions to CWS hinge on institutional reforms, robust financing, and strong political commitment. The discussion highlights partial measures to mitigate risks, such as on-site residual boosting, pressure management, and District Metered Areas. Ongoing efforts to achieve the United Nations Sustainable Development Goals (SDG 6.1) necessitate clearer metrics for the continuity of water supply and improved monitoring frameworks. Overall, an integrated approach combining technical upgrades, effective governance, and community engagement is critical to guaranteeing equitable access to safe water.

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Introduction

Access to safe drinking water remains an enduring challenge in developing countries, particularly in rapidly urbanizing regions such as India, many parts of Sub-Saharan Africa, and elsewhere in the Global South. In these contexts, water is sometimes delivered through networks that operate intermittently rather than continuously, generating numerous technical, equity, and health implications. Continuous water supply (CWS), the norm in most high-income countries, contrasts with intermittent water supply (IWS), in which water is available only for limited hours per day or even a few times per week. This literature review synthesizes insights from numerous research papers on water supply systems—particularly from sources focusing on India, parts of Asia, sub-Saharan Africa, and other developing regions—and weaves them into a comprehensive discussion of challenges, solutions, and lessons learned. The review endeavors to address the following questions:

- What are the main causes and characteristics of intermittent water supply systems in developing countries?
- How do intermittent versus continuous systems compare in terms of equity, efficiency, and water quality?
- Which technical and governance interventions have succeeded (or failed) in ensuring equitable water provision in low-resource settings?
- What lessons can be extracted from the experiences of first-world countries that historically faced, but have largely resolved, water supply issues?

We will draw heavily on research from India, the Middle East, sub-Saharan Africa, and comparative studies from elsewhere [1-6]. The overarching aim is to highlight how the interplay of governance, engineering, social, and environmental factors influences water-supply continuity and equity. To meet the objective of appealing to a technical global water community, we include mathematical models of household demand, references to distribution hydraulics, and frameworks for assessing water supply system performance. Tables and conceptual figures—though not fully rendered here—will be described to illustrate key findings. We conclude by recommending strategies to enhance water supply continuity and equitable access, particularly in the face of climate change and rapid urban expansion.

Overview of Urban and Rural Water Supply: Definitions and Historical Perspectives

Urban Water Supply

Urban water supply encompasses large networks that source water from rivers, lakes, reservoirs, or aquifers, and distribute it through extensive piping systems to households, commercial, and industrial consumers [1]. Historically, in high-income nations (the "first world"), municipal water systems evolved to deliver continuous pressurized water to end-users, fulfilling high-level performance standards. This was achieved through robust governance structures, substantial capital investment, and an emphasis on systematic operation and maintenance [7]. In many low- and middle-income countries, however, the combination of rapid population growth, underinvestment, water scarcity, and governance deficits has led to partial or complete reliance on intermittent networks [8]. At least 300 million urban dwellers worldwide receive water intermittently [9]. Indeed, for a number of cities in India and sub-Saharan Africa, the distribution system fails to maintain 24-hour pressure, leading to "rotational" water supply that runs for a few hours in one zone before being switched to another [2,6].

Rural Water Supply

While cities garner significant policy attention, rural areas in developing countries also struggle with water security. Rural populations may rely on shallow wells, handpumps, springs, or small-scale gravity-fed or pumped piped networks. According to Post et al., rural populations, especially in South Asia and sub-Saharan Africa, frequently face inequalities in source reliability and water quality [10]. Rural communities experience both environmental (e.g., seasonal droughts, over-extraction of groundwater) and governance challenges (e.g., limited cost recovery, incomplete local institutional capacity), which hinder the transition to stable, continuous water services [11]. In many instances, small-town water supply systems mimic the "semi-urban" pattern of limited daily or weekly piped flow, forcing communities to cope with unsafe or inconvenient alternative sources such as water vendors [12,13].

Historical Emergence of Intermittent Water Supply

Intermittent water supply often emerges from expansions of networks beyond design capacity, inadequate revenue collection (leading to poor maintenance), and water resource scarcity [14]. Totsuka et al. identified how technical scarcity (leakage and infrastructure constraints), economic scarcity (limited capital to upgrade treatment and distribution), and absolute scarcity (inadequate raw water resources) push many utilities to adopt IWS as a rationing mechanism [15]. In such contexts, distributing water for a few hours each day or week is seen as a necessary compromise to spread limited supplies across large populations [8]. Over time, the repeated pressurization and depressurization accelerates pipe corrosion, fosters intrusion of contaminants, and exacerbates overall network deterioration [2].

Characteristics and Mechanisms of Intermittent Water Supply

Defining Intermittent Supply

Intermittent water supply (IWS) can be broadly defined as a piped water system in which water is available for less than 24 hours per day, typically on a scheduled or unscheduled rotation [16]. The duty cycle (i.e., fraction of the day that supply is pressurized) varies widely. In some areas, water runs for only 2–4 hours per week, whereas in others it may be nearly continuous, with short daily interruptions [2]. On the engineering side, the cyclical pressurization imposes transient flows that cause flow reversals, surges, intrusion, and partial pipe drainage [17].

Hydraulic Modeling Insights

Many scholars have sought to model IWS to predict water quality and quantity outcomes. Conventional continuous supply models assume that each node in the pipe network is pressurized at all times, and household demand is fully satisfied at that node's available pressure [18]. By contrast, IWS hydraulic simulations must capture time-varying pressurization and partial filling of pipes [19]. A macroscopic approach, based on the concept of aggregated supply, has been proposed by Taylor et al., who modeled total system flow as the sum of "effective demand" (pressure-dependent) and "aggregate leakage [19]." In many IWS networks:

$$\text{Total Water Supplied } (V_T) = V_D + V_L$$

where V_D is the volume demanded by consumers (when their demand is met), and V_L is the leakage volume, often highly pressure-dependent [19]. Because intermittent networks are not fully pressurized, the average system pressure can drop, reducing both leakage and consumer supply in unpredictable ways.

Contamination Pathways and Water Quality Impacts

One of the gravest concerns with intermittent distribution is the loss of hydraulic integrity, which allows for intrusion of contaminants. Researchers have documented that stagnant water in empty pipes can be contaminated through cracks or cross-connections, especially if external infiltration occurs when the pressure is below ambient [2,20]. Frequent re-pressurization can loosen deposits and biofilms, creating water discoloration and heightened microbial loads (Tokajian & Hashwa, 2003). As a result, measurement campaigns in IWS often observe higher microbial indicators (e.g., fecal coliform, E. coli) at household taps than at the utility's reservoir outlet [2]. For instance, in Hubli–Dharwad, India, 32% of intermittent household tap samples were E. coli positive, compared to only 12% from the continuous pilot area [2]. Although consumer-level storage can mitigate water shortages, it can also expose water to secondary contamination inside household tanks [20].

Equity, Governance, and Socio-Political Dimensions

Access Inequality

Studies confirm that IWS often correlates with inequitable service distribution. Households in wealthier, centrally located neighborhoods frequently receive more hours of supply, while peri-urban or informal settlements see lower pressures and shorter durations. McKenzie and Ray found that in Indian cities, neighborhoods that house higher-income groups often benefit from better infrastructure, leaving the poor with intermittent or no connections [1,21]. This inequity is exacerbated by water theft, illegal tapping, and political influence, which can skew distribution patterns [22].

Governance Failures

The inability to provide continuous supply is also tied to systemic governance shortcomings: low cost recovery, lack of investment in leakage repair, corruption, or a policy focus on network extension over service quality [7]. Municipal governments may face short electoral cycles, disincentivizing long-term system rehabilitation (Jones et al., 2014). The "downward spiral" identified by Galaitsi et al. posits that chronically low tariffs reduce the revenues needed to repair infrastructure, leading to more leakage and supply disruptions, which in turn prompt households to invest privately in storage or wells—further reducing utility revenue and sustainability [8].

Community Coping Strategies

When faced with unreliable or inadequate supply, households adopt multiple coping strategies, such as installing overhead tanks, suction pumps, or private wells [23]. While these solutions help households secure short-term water needs, they undermine the financial viability of public utilities and can induce groundwater over-extraction [24]. Meanwhile, the poorest households—lacking the capital for private infrastructure—endure the worst service. They either wait in long queues or pay high prices to water vendors [6]. In some communities, social friction arises as unscrupulous neighbors manipulate valves to divert flow or utility staff accept bribes to provide longer supply hours in certain areas [7].

Converting Intermittent to Continuous Supply

An increasing body of evidence suggests that universal conversion to CWS is feasible and beneficial under specific conditions [25]. However, conversion requires major upfront investments to repair or replace decaying infrastructure, reduce leakage, and expand water treatment capacity [1]. City-level case studies from Hubli–Dharwad (India) demonstrated improved public health outcomes, greater willingness to pay among consumers, and reduced coping costs once continuous supply was introduced in pilot zones [2]. The pilot's success was predicated on top-down political support, robust financing from the World Bank, and partnership with local NGOs for community education.

Technical Solutions: Lessons from Various Industries

Infrastructure Leakage Management

Drawing from the water industry's best practices, pressure management and District Metered Areas (DMAs) are widely used in high-income countries to detect and mitigate leaks (Lambert, 2002). In an IWS context, the value of DMAs is contested, since intermittent flow confounds night-flow measurements used to estimate leakage (Klingel, 2012). Nevertheless, some developing utilities are experimenting with partial pressure management to maintain a minimal positive pressure even in off-peak times, thus reducing contamination [26]. The introduction of robust Supervisory Control and Data Acquisition (SCADA) systems can help track flows more precisely and allocate water, but resource constraints and unreliable power supply hamper SCADA's adoption [16].

Water Treatment Options

Efficient water treatment upstream is crucial to ensure that infiltration does not degrade water quality further. However, water utilities operating on limited budgets sometimes skip advanced treatment processes or lack adequate disinfection. If water is not fully disinfected before the intermittent distribution, or if the chlorine residual decays quickly due to high chlorine demand in corroded pipes, the finished water is more susceptible to microbial regrowth [27]. Newer approaches (e.g., chloramination, on-site residual boosting at strategic nodes) can help sustain disinfectant levels, though each approach poses design and cost challenges in resource-poor contexts [3].

Household-Scale Filtration and Disinfection

Given the reality of contamination within IWS networks, many communities rely on point-of-use (POU) water treatment to ensure potability, including boiling, chlorination, and filtration methods [28]. Although these can reduce the health risks associated with IWS, POU interventions shift the burden of water treatment to households. The poorest households often cannot afford robust POU systems or the recurring cost of disinfectants [3]. By contrast, some "solutions from various industries"—like the beverage sector's low-cost filtration and disinfection technologies—might help scale up neighborhood-level or kiosk-based water disinfection. Nonetheless, sustaining these kiosk-based approaches requires stable business models and acceptance by local communities [29].

Comparative Experiences: High-Income vs. Developing Countries

Lessons from First-World Countries

In the United Kingdom, the United States, and much of Europe, intermittent water supply was phased out in the early 20th century through a combination of public health reforms, robust economic growth, municipal consolidation of water services, and advanced engineering [30]. The transition to continuous supply hinged on public pressure for better sanitation and the availability of capital to modernize distribution systems. Interestingly, some older U.S. cities also faced "partial intermittency" or rotational supply in the 19th century, but this was rectified as soon as new reservoirs and trunk mains were built [31]. Continuous pressurization eventually became the standard, mandated by public health regulations that recognized the contamination risk associated with negative pressures.

Factors Behind Failed Reforms in Developing Countries

Despite the recognized benefits of continuous supply, many attempts at reforms have stalled. Among the reasons are political meddling (with tariff setting), unclear property rights in informal areas, and the difficulty of financing major capital expansions [32]. Bids for private sector participation often run into public opposition if proposed tariff hikes are seen as unjust [7]. In some African cities, short project timelines and donor-driven targets for quick network expansion overshadow the equally crucial need to maintain or upgrade existing infrastructure [5]. Nigeria's attempts at privatization in the early 2000s, for instance, saw significant local resistance and minimal improvement in continuous supply [33].

Hybrid Service Models

Hybrid models—public–private partnerships, local utility–NGO alliances, and community-based management—have delivered partial improvements. For instance, in Kenya, some communities in peri-urban Nairobi formed water user associations that coordinate with the city's water utility to manage local distribution. These associations often reduce non-revenue water while extending coverage to "missing middle" areas [29]. However, these piecemeal solutions rarely achieve universal, continuous supply but can be stepping stones toward improved reliability.

Rural–Urban Nexus: Addressing Inequalities Across Regions

Rural–Urban Gaps

Reports indicate that, on average, rural areas in low-income countries continue to lag behind their urban counterparts in having improved water sources [11]. However, given that many cities have IWS, the difference between "improved" urban water and "unimproved" rural supply is often not so large in practice. Post et al. argue that focusing solely on official "improved vs. unimproved" categories may mislead policy makers by overlooking massive coverage of intermittent or unpressurized systems [10]. The Joint Monitoring Programme (JMP) guidelines highlight the need to measure both the continuity (availability) and the water quality dimensions of supply [34].

Migration and Peri-Urban "Intermittent Enclaves"

Rapid urbanization in countries like India has resulted in sprawling peri-urban areas that combine low-density rural elements with pockets of high-density settlements [1]. These peri-urban zones often exhibit severe water supply fragmentation: some households rely on small piped systems or tanker trucks, while wealthier enclaves link to the municipal network [6]. Because of limited administrative oversight, these areas can remain "off-grid" or unregulated for years, compounding the complexities of achieving universal continuous supply. The notion of an "intermittent enclave" emerges: a sub-area with partial but not fully integrated service, caught between rural and urban governance structures, thus perpetuating IWS [5].

Case Examples: India, Sub-Saharan Africa, and Others

India

- **Hubli–Dharwad Pilot:** A well-documented pilot in Hubli–Dharwad involved upgrading a part of the network to continuous pressurization. Kumpel and Nelson found that the pilot area showed consistently better microbial water quality at the tap (less E. coli contamination) and significantly reduced household coping costs [2]. The pilot's success hinged on rehabilitated infrastructure, reliable volumetric metering, and tariff adjustments.
- **National Context:** Across most Indian cities (e.g., Bangalore, Chennai, Delhi), intermittent supply remains the default. Estimations show that only a small percentage of the population—often living in neighborhoods with direct pumping—experience near-continuous supply [1]. Despite major government schemes (e.g., Jawaharlal Nehru National Urban Renewal Mission (JNNURM)) funneling billions into water infrastructure, many projects have not drastically improved daily hours of supply [35]. Political preferences for network expansion over maintenance hamper the shift to 24×7 service.

Sub-Saharan Africa

- **Rapid Urbanization:** In many major African cities—Lagos, Dar es Salaam, Lusaka—utilities are underfinanced, and water sources are increasingly stressed [6]. Intermittent supply is widespread, with daily supply durations often below 10 hours [14]. While some African utilities have tried pilot programs to reduce non-revenue water and improve continuity, few have scaled up [36].
- **The Impact of Non-Government Initiatives:** NGOs frequently implement mini-networks or point source improvements. While these interventions may enhance local reliability, they often lack the scale or integrated planning needed for citywide continuous service [29]. In peri-urban Kibera (Nairobi, Kenya), small water kiosk franchises are bridging the coverage gaps, though the water is sometimes delivered intermittently or is pressurized only on certain days [5].

Middle East and North Africa (MENA)

Wars and water resource conflicts across MENA have pushed many cities to ration supplies. For instance, Byblos (Lebanon) and Nablus (Palestine) commonly see 10–12 hours of water supply every other day [4]. Infrastructure constraints and political strife hamper major overhauls, though local staff have experimented with re-chlorination boosters and zone-based scheduling [4]. Chronic IWS in these cities raises contamination risks as pipes remain depressurized for extended periods, especially in summer.

Strategies for Improving Equity and Service Quality

Tariff Reforms and Subsidies

Economic instruments can encourage sustainable water use and fund maintenance if properly aligned with cost-recovery. However, in many developing contexts, water prices remain too low to finance capital improvements, fueling the intermittent supply cycle [8]. Cross-subsidies can be effective if the utility implements progressive block tariffs and ensures that the poorest can afford a basic level of service [37]. Nonetheless, incomplete metering in many IWS systems complicates volumetric billing [1]. The result is that more affluent households that can store water or pump from the main lines ironically pay less per unit of water than do the poor, who buy from vendors at high markups [6].

Addressing Non-Revenue Water

Non-revenue water (NRW), which includes leakage and unmetered consumption, can exceed 50% in some IWS utilities [1]. Tools like District Metered Areas, active leak control, and improved billing systems are proven in first-world contexts but face operational difficulties in IWS. For instance, when the network is only pressurized a few hours daily, nighttime flow analysis becomes infeasible. Still, partial solutions—like intermittent "zoning" combined with flow meters for each subzone—can help to locate major leaks or bursts [38]. The effort to systematically reduce NRW can free up additional water resources for continuous supply, as documented in select pilot projects in Jordan and India [1].

Infrastructure Rehabilitation

Trenchless technologies for pipe replacement, advanced materials for leak-resistant joints, and internal pipe linings to reduce corrosion have been successfully deployed in high-income cities for continuous pressurization [39]. Even partial adoption of these upgrades can reduce infiltration and exfiltration in IWS, mitigating water quality risks. However, funding remains a major obstacle in many developing countries. The scale of upgrade needed to convert to continuous supply can be overwhelming, especially when combined with the expansions needed to meet population growth [21]. Gradual replacements, starting in pilot zones, can yield incremental improvements that demonstrate feasibility.

Community and Utility Partnerships

Active community engagement can heighten accountability and encourage prompt leak reporting (Biswas & Tortajada, 2010). Local water committees can oversee distribution scheduling, though the risk of local corruption arises. Partnerships with neighborhood associations have proven successful in some contexts (e.g., the Orangi Pilot Project in Karachi, Pakistan), where communities co-finance small distribution improvements, culminating in near-continuous supply in some wards [40]. Yet these successes require consistent external support and a stable organizational framework.

The Way Forward: Toward Equitable Continuous Supply

The Role of Climate Change

Climate change will intensify water scarcity in many regions, placing additional pressure on utilities that already struggle to supply water continuously [41]. Drought-prone areas may be forced to adopt more rotational supply regimes if reservoir levels drop. However, well-designed integrated water resource management can mitigate extremes. For instance, if utilities invest in demand management, expanded storage infrastructure, and diversified supply sources (groundwater recharge, reuse, etc.), they are better positioned to deliver continuous supplies even in drought years [42].

Evolving Monitoring and Regulation

SDG 6.1 emphasizes "universal and equitable access to safe and affordable drinking water." The recommended service level includes continuity of supply, but global data sets often conflate "piped on premises" with "continuous" [34]. Tools such as the Intermittent Water Supply Index (IWSI) or daily duty cycle measurements can offer standardized ways to report service reliability. If regulatory bodies systematically require reporting of supply durations and water quality indicators, it becomes possible to identify the worst-off areas and direct financial resources accordingly [8].

The Human Right to Water

From a rights-based perspective, intermittent supplies often fail to provide an adequate, reliable quantity of water, undermining the full realization of the human right to water [43]. Governments have an obligation to ensure that all citizens have at least a basic supply, which can be undermined by IWS if supply schedules are unpredictable or short. Legal frameworks that define quantity and continuity as part of the right to water can empower civil society to demand improved services [22]. Tools such as public interest litigation (as used in India) can push local governments to accelerate reforms, although success depends on the quality of jurisprudence and enforcement.

Conclusion and Recommendations

Intermittent water supply systems—serving at least 300 million people globally, possibly many more—represent a pressing challenge for water security, public health, and social equity in developing countries. These systems often emerge from a blend of water scarcity, network overextension, governance deficiencies, and inadequate financing for maintenance and repair. Once established, IWS can develop self-reinforcing cycles wherein utilities lose revenue and customers lose confidence, leading to further disrepair and coping strategies.

However, a growing body of evidence and practical case examples demonstrate that the transformation to continuous water supply is both achievable and beneficial, provided utilities adopt comprehensive approaches:

- **Leakage Control and Demand Management:** Reducing non-revenue water liberates precious resource volumes, enabling extended supply durations and improved pressure. Strategic pressure management, or phased enhancements like District Metered Areas (where feasible), are powerful levers.
- **Institutional Strengthening:** The shift from IWS to CWS requires stable tariffs, predictable government subsidies, corruption reduction, and transparent oversight. Policymakers must shift focus from short-term network expansions toward maintaining core infrastructure quality and reliability.
- **Targeted Community Engagement:** Partnerships between utilities and local communities or NGOs can expedite leak detection, promote POU water treatment, and help clarify the benefits of new approaches like continuous supply pilot zones.
- **Incremental Technical Upgrades:** While immediate network-wide conversions may be expensive, pilot projects can test upgrades to trunk mains, re-chlorination stations, and consistent pressurization in a designated subzone. Demonstrated success can spur political buy-in and consumer willingness to pay.
- **Better Data and Benchmarking:** International donors and national regulators must insist on uniform metrics for measuring continuity (like duty cycle, hours of supply, or IWSI) and water quality outcomes. The same metrics can track progress toward SDG 6.1 and highlight high-need areas.

In first-world countries, the elimination of IWS was an incremental historical process underpinned by robust financing, strong municipal capacity, and public demand for safe water. Developing countries, faced with more acute resource constraints, still can replicate these lessons by tailoring technical and governance reforms to their local context, building robust revenue models that ensure sustainability, and prioritizing the worst-off communities first. Achieving universal, equitable, and continuous water supply is both a moral imperative—aligned with the human right to water—and a practical strategy for enhancing public health, economic productivity, and social well-being [44].

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