QUANTITATIVE ASSESSMENT OF MUNICIPAL WATER SUPPLY AND SOCIO-SPATIAL FACTORS INFLUENCING URBAN WATER CONSUMPTION IN VIENTIANE CAPITAL, LAO PDR (2020-2025)

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ABSTRACT

Rapid urban growth has intensified pressures on the municipal water-supply infrastructure in Vientiane Capital, Lao PDR. While total annual water production capacity has expanded, achieving equitable and reliable service remains a critical challenge. This study integrated multi-year operational records from eight water treatment plants (WTPs) (2020–2025) with a structured questionnaire survey and geographic coordinates of 360 households. The analysis assessed spatial-temporal production trends, distribution-to-abstraction efficiency, and household-level service conditions, including geographic accessibility to treatment infrastructure. Findings reveal that total annual abstraction increased from 111.99 million cubic metres (Mm^3) in 2020 to 137.15 Mm^3 in 2025 (CAGR 4.14%), while total annual distribution rose from 98.38 Mm^3 to 128.82 Mm^3 (CAGR 5.54%). Dongmakkhai 2 emerged as the principal contributor to this expansion, accounting for approximately 29.2% of the municipal water distribution by 2025. Spatial-accessibility analysis indicated a mean household distance of 12.03 km to the nearest WTP, with 65.6% of households located within 10 km of treatment facilities. Despite widespread physical access with 88.9% of households using public piped water service reliability is constrained by hydraulic factors; 67.2% of households reported low water pressure, and 89.4% identified pressure improvement as a primary service priority. Overall satisfaction was high (81.9%), yet 18.1% of households reported moderate satisfaction or dissatisfaction, suggesting that geographic proximity and network connection alone do not guarantee adequate hydraulic performance. The study provides a holistic diagnostic framework by linking supply-side production trends with demand-side geospatial evidence. Results emphasize the necessity of shifting urban water-supply planning from a focus on production capacity to an integrated strategy encompassing network-level pressure management, systematic leakage control, and spatially targeted infrastructure investment, all of which are essential for advancing Sustainable Development Goal 6.

Keywords: *Urban water supply; Geospatial accessibility; Service satisfaction; Hydraulic performance; Water treatment plants; Vientiane Capital - Lao PDR.*

1. INTRODUCTION

Rapid urbanization, economic transition, and population growth in Southeast Asian capital cities have placed unprecedented pressure on urban water supply systems (Baird, 2024). As cities transform from rural-agrarian landscapes into dense commercial and residential hubs, the geographic distribution of water demand shifts dynamically, creating significant mismatches between municipal water availability and localized consumption patterns (Grenade et al., 2016; UNICEF & WHO, 2020).

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Urban water management in rapidly growing cities requires robust analytical frameworks that integrate hydrological data with socio-spatial indicators. Geographic Information Systems (GIS) have proven effective in supporting water resource assessments, hazard mapping, and infrastructure planning across diverse contexts. For instance, GIS-based approaches have been applied to evaluate water demand suitability in Vientiane Capital using fuzzy analytical hierarchy process models (Singharaj et al., 2026), predict water quality indices in Thailand's Tha Chin River (Promhan & Pilailar, 2025), and delineate flood hazard zones in Indonesia's Tuntang watershed (Novita et al., 2023). For developing countries like Lao PDR, managing municipal water supplies is not merely a technical challenge of expanding engineering infrastructure but a complex socio-spatial issue. Sustainable urban water management requires balancing physical resource extraction with the socio-demographic activities of urban dwellers (Sudha et al., 2025; UNFPA, 2025). Vientiane Capital, the political, economic, and administrative heart of Lao PDR, serves as a critical focal point for studying these urban water dynamics. Driven by national economic policies and regional integration, the city has experienced rapid horizontal expansion, causing residential zones to encroach onto agrarian and peri-urban spaces (Hue et al., 2016; Thailand Environment Institute, 2017).

The state-owned water utility, Nam Papa Nakhone Luang (NPNL), has consistently invested in network capacity to match this outward urban sprawl (UN-HABITAT, 2010). Consequently, water security in Vientiane Capital presents a spatial paradox: while the city is situated alongside the Mekong River a massive regional surface water source many urban and peri-urban communities suffer from unequal access, low water pressure, and localized water shortages (Lao Statistics Bureau, 2022).

To address these vulnerabilities, academic research must look beyond simple city-wide consumption averages. Water security studies increasingly rely on integrated spatial and quantitative assessments that examine both the supply side dynamics of WTPs and the demand-side socio-spatial factors of consumer households (Zheng et al., 2023; Pichis-García & Cueva-Rodríguez, 2026). On the supply side, tracking longitudinal trends of water abstraction and distribution is vital for revealing system efficiencies and operational gaps. On the demand side, household characteristics such as family size, income, access conditions, and subjective satisfaction determine actual water-use behavior and public willingness to support service improvements (Fielding et al., 2012; Cook et al., 2016; World Bank, 2020).

In Vientiane Capital, the municipal water grid relies on a multi-nodal network of eight treatment plants, including historical plants like Kaolieo and Chinaimo, as well as newer facilities like Dongmakkhai 2, Dongbang, Seandin, and Thaduea. However, empirical studies that track the performance, abstraction-to-distribution gaps, and capacity trends of these individual plants over a multi-year timeline are limited. Furthermore, there is a severe shortage of academic literature linking these quantitative engineered supply metrics with micro-level household survey data and geospatial accessibility indicators (i.e., distance to infrastructure) across Vientiane's shifting urban-rural gradient. Most existing local water studies focus on rural agricultural irrigation or general chemical water quality (WHO, 2016; 2017), leaving the structural relationship between municipal water infrastructure and socio-spatial consumer profiles unexamined. To bridge this literature gap, this study provides a comprehensive quantitative and socio-spatial assessment of the water supply-demand nexus in Vientiane Capital from 2020 to 2025. Specifically, the research objectives are to quantitatively analyze the longitudinal trends of raw water abstraction and treated water distribution across eight major water treatment plants servicing Vientiane Capital, to evaluate system performance and operational gaps between water production and delivery, to assess household-level access, service continuity, pressure reliability, and overall satisfaction using a geographically referenced survey of 360 households and to examine the spatial accessibility of households to water-supply infrastructure as a determinant of service condition.

By integrating physical water-supply tracking with geospatial household-survey data, this paper offers a holistic diagnostic tool for urban planners, environmental engineers, and policymakers in Lao PDR, supporting the sustainable targets of United Nations Sustainable Development Goal 6 (SDG 6) in rapidly expanding secondary cities of Southeast Asia.

2. STUDY AREA

2.1. Geographical Location and Physical Characteristics

Vientiane Capital, the political, economic, and administrative center of the Lao People's Democratic Republic (Lao PDR), is situated in the central-western part of the country within the fertile alluvial plains of the Mekong River basin. The study area lies approximately between latitudes 17°46' N to 18°28' N and longitudes 102°13' E to 103°03' E (**Fig. 1**). Vientiane Capital shares its southern and western borders with Thailand (Nong Khai and Loei provinces) along the Mekong River, while bordering Vientiane Province to the north and Bolikhamsai Province to the east. Base map data for the study area were generates using ArcGIS 10.8, with layers courtesy of OpenStreetMap (licensed under School of Information and Communication technology, University of Phayao)

The study area encompasses nine administrative districts: Chanthabuly, Sikhottabong, Xaysetha, Sisattanak, Hadxayfong (collectively regarded as the core urban districts), and Saysettha, Outhoomphone, Pakngum, and Sangthong (designated as peri-urban and rural districts). The total administrative area spans approximately 3,920 km², characterized by a relatively flat to gently undulating topography in the southern and western plains, transitioning into low hills in the northern and eastern fringes, with elevations ranging from 160 to 350 meters above mean sea level (Ministry of Natural Resources and Environment [MoNRE], 2020).

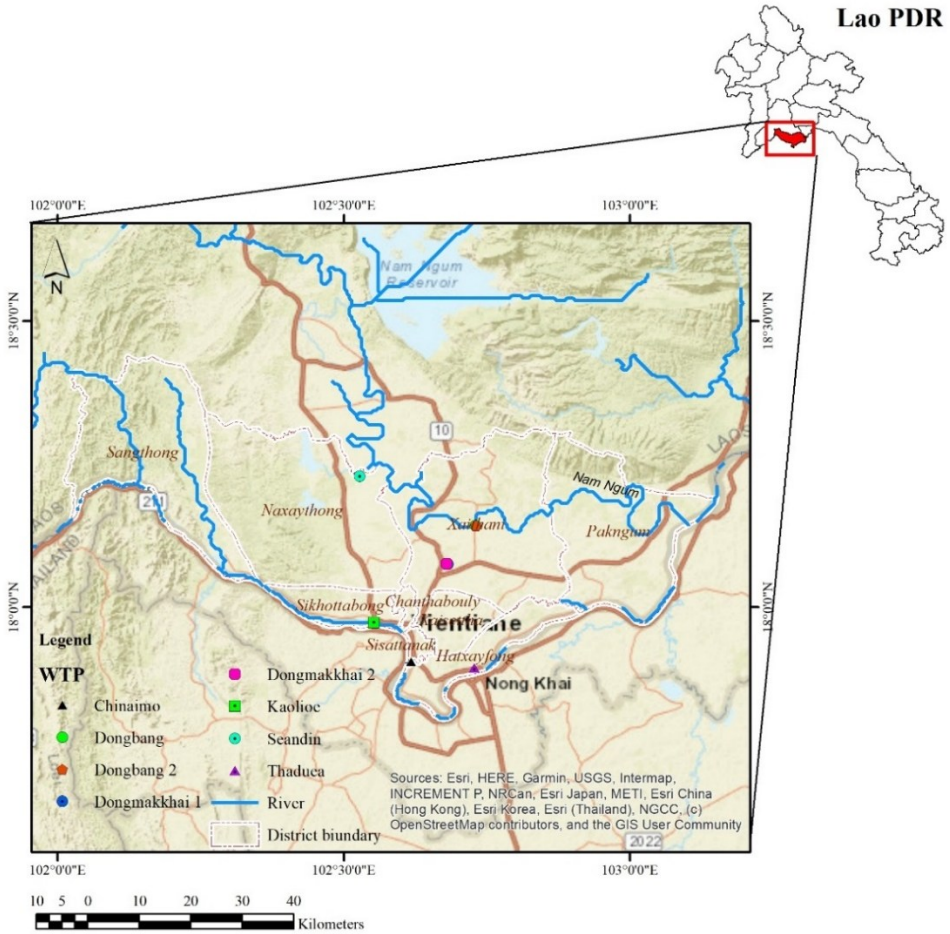

Fig. 1. Geographical location map of Vientiane Capital showing administrative districts and hydrological network, source: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, OpenStreetMap contributors and the GIS User Community.

2.2. Climatic and Hydrological Conditions

The climatology of Vientiane Capital is classified as a tropical monsoon climate (Aw under the Köppen climate classification), governed by the southwest monsoon (rainy season) from May to October, and the northeast monsoon (cool-dry season) from November to April (Department of Meteorology and Hydrology, 2022). The mean annual rainfall fluctuates between 1,500 mm and 1,800 mm, with more than 80% concentrated during the wet season, causing significant seasonal variability in surface water discharge. The annual average temperature exhibits a narrow thermal range of 24°C to 32°C, with April being the hottest month (maximum temperatures exceeding 38°C) and January being the coolest.

From a hydrological standpoint, Vientiane Capital heavily relies on the Mekong River system and its primary local tributaries namely the Nam Ngum, Nam Lik, and Houay Mark Hiao rivers for ecological restoration, agricultural irrigation, and municipal water production (Lacombe et al., 2020). The Mekong River serves as the primary raw water source for the state-owned water utility enterprise, state-owned NPNL. Additionally, shallow and deep aquifers within the sedimentary alluvial deposits serve as vital secondary water sources, particularly in peri-urban zones where municipal piped water networks remain underdeveloped (Coulon et al., 2021).

2.3. Demographics, Socio-Spatial Dynamics, and Urban Expansion

During the designated assessment period (2020-2025), Vientiane Capital has experienced unprecedented demographic shifts and rapid, horizontal urban sprawl. The population grew from approximately 828,000 in 2020 to over 950,000 by 2025 (Lao Statistics Bureau, 2023). This rapid population increase, fueled by rural-to-urban migration, is highly concentrated in the five core urban districts, leading to high population densities (exceeding 1,500 persons/km^2 in Sisattanak and Chanthabuly).

This demographic density coincides with significant socio-spatial disparities. While the inner-city core boasts highly developed infrastructure and nearly universal access to piped water networks, the outer peri-urban zones are characterized by fragmented urbanization, transitioning land use from agricultural paddies to residential estates, and a high reliance on groundwater extraction (Gumma et al., 2023; Nakamura, 2019). The rapid transformation of the spatial landscape has altered the urban microclimate and significantly increased the spatial heterogeneity of domestic, commercial, and industrial water consumption patterns, rendering Vientiane Capital a crucial case study for analyzing water resource availability against socio-spatial determinants.

3. DATA AND METHODS

3.1. Data Acquisition and Sources

The research utilizes a dual-source dataset to investigate the water supply-demand nexus in Vientiane Capital.

1) Municipal Supply Data

Longitudinal operational records for eight WTPs; Kaolieo, Chinaimo, Dongmakkhai 1 & 2, Dongbang 1 & 2, Seandin, and Thaduea were obtained from NPNL for the period 2020-2025. Data include annual raw water abstraction (Mm^3) and treated water distribution volumes (Mm^3), which are critical for calculating system efficiencies.

2) Socio-Spatial Household Survey

A structured questionnaire was administered to 360 households. The survey collected demographic data, water-source reliance, connection types, service continuity, pressure reliability, and overall satisfaction. To facilitate spatial analysis, geographic coordinates (X, Y; UTM zone 48N, WGS 1984) were recorded for each household using GPS-enabled devices.

3.2. Geospatial Analysis of Service Accessibility

To evaluate the spatial relationship between infrastructure and consumer access, we integrated the household coordinates with the locations of the eight WTPs.

1) Euclidean Distance Mapping

We calculated the shortest straight-line distance from each household (i) to its nearest WTP (j) using the Euclidean distance formula:

$$d_i = min_j \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (1)$$

where (x_i, y_i) are the coordinates of the household and (x_j, y_j) are the coordinates of the WTP.

2) Spatial Categorization

Households were grouped into distance bands (<5 km, 5 to <10 km, 10 to <20 km, 20 to <40 km, and ≥40km). This spatial categorization serves as a geographic accessibility indicator to identify potential service inequalities across the city's urban-rural gradient.

To visualize the spatial-temporal dynamics of water abstraction and distribution intensities, Kernel Density Estimation (KDE) was employed using ArcMap 10.8. This technique generates a continuous density surface from point-based operational data, effectively identifying geographic hotspots where water production and delivery activities are concentrated. The analysis utilized a 10 km search radius to capture the spatial intensity variations across the Vientiane Capital municipal network from 2020 to 2025.

3.3. Statistical Modeling

1) System Performance Metrics

Abstraction-to-distribution gaps were calculated to estimate operational efficiency. The Compound Annual Growth Rate (CAGR) was employed to track longitudinal production trends.

2) Ordinal Logistic Regression (OLR)

To assess determinants of service satisfaction, an OLR model was constructed. The model estimates the probability of household satisfaction levels (Y) based on a set of socio-spatial predictors (X):

$$logit[P(Y_i \leq j)] = \alpha_j - (\beta_1 HS_i + \beta_2 INC_i + \beta_3 GW_i + \beta_4 CS_i + \beta_5 LP_i + \beta_6 WQ_i + \beta_7 DIST_i) \quad (2)$$

where Y_i denotes the ordinal level of satisfaction, ranging from dissatisfied to very satisfied; HS_i and INC_i represent household size and household income, respectively; GW_i, CS_i, LP_i, and WQ_i denote groundwater use, water supply continuity, the experience of low water pressure, and perceived water quality, respectively; and $DIST_i$ refers to the GIS-derived distance from each household to the nearest WTP.

To examine the determinants of household water-service satisfaction, an OLR model was employed. The descriptive statistics of the variables included in the model are presented in **Table 1**. The experience of low water pressure was identified as a significant determinant of household dissatisfaction, reflecting the critical influence of hydraulic service levels on consumer perceptions.

Table 1.
Descriptive statistics of variables used in the Ordinal Logistic Regression model (N=360).

Variable	Definition/Unit	Mean/Freg	Stds. Dev
Overall satisfaction (Ordinal)	1: Slightly satisfied to 4: Very satisfied	2.94	0.85
Geospatial distance (Continuous)	Distance to nearest WTP (km)	12.03	9.45
Low pressure experiece (Binary)	1: Yes, 0: No	0.67	0.47
Continuous 24th supply (Binary)	1: Yes, 0: No	0.78	0.42
Household size (Continuous)	Number of persons	3.56	1.21

3) Model Validation

Model adequacy was evaluated using the Likelihood Ratio Chi-Square test, Nagelkerke Pseudo-R^2, and the Test of Parallel Lines. Spatial distribution of satisfaction and service problems was visualized using GIS mapping to identify potential service hotspots. Statistical significance was set at $p < 0.05$.

4. RESULTS

4.1 Spatial-Temporal Dynamics of Water Abstraction and Distribution (2020–2025)

The quantitative assessment of municipal water supply dynamics in Vientiane Capital from 2020 to 2025 reveals a major structural and geographical shift in the city's water production regime. Drawing on long-term administrative records from the state-owned utility NPNL, total municipal water distribution across all active facilities grew from 92.09 Mm^3 in 2020 to 128.88 Mm^3 by 2025. This represents an overall 39.95% increase in municipal supply distribution capacity over the 6-year study period (**Fig. 2** and **Fig. 3**). This rapid expansion has changed the geographic distribution of water production, shifting the city's primary water sources away from the traditional Mekong River mainstream toward inland rivers and groundwater networks in the north and northeast.

4.1.1. The Stabilization of the Central Mekong Backbone (Chinaimo and Kaolieo)

Historically, the urban core of Vientiane Capital relied on the Chinaimo and Kaolieo WTPs, both of which abstract surface water directly from the mainstream Mekong River. The Kaolieo WTP maintained stable abstraction, decreasing marginally from 24.15 Mm^3 in 2020 to 24.05 Mm^3 in 2025 (CAGR = -0.08%). Distribution volumes increased slightly to 23.16 Mm^3 (CAGR = +0.42%). Similarly, the Chinaimo WTP exhibited minimal change, with abstraction rising from 32.47 Mm^3 to 32.57 Mm^3 (CAGR = +0.06%) and distribution reaching 29.92 Mm^3 (CAGR = +0.31%). Both plants illustrate the structural limits of the central Mekong-based backbone, which has reached near-capacity in supporting urban expansion.

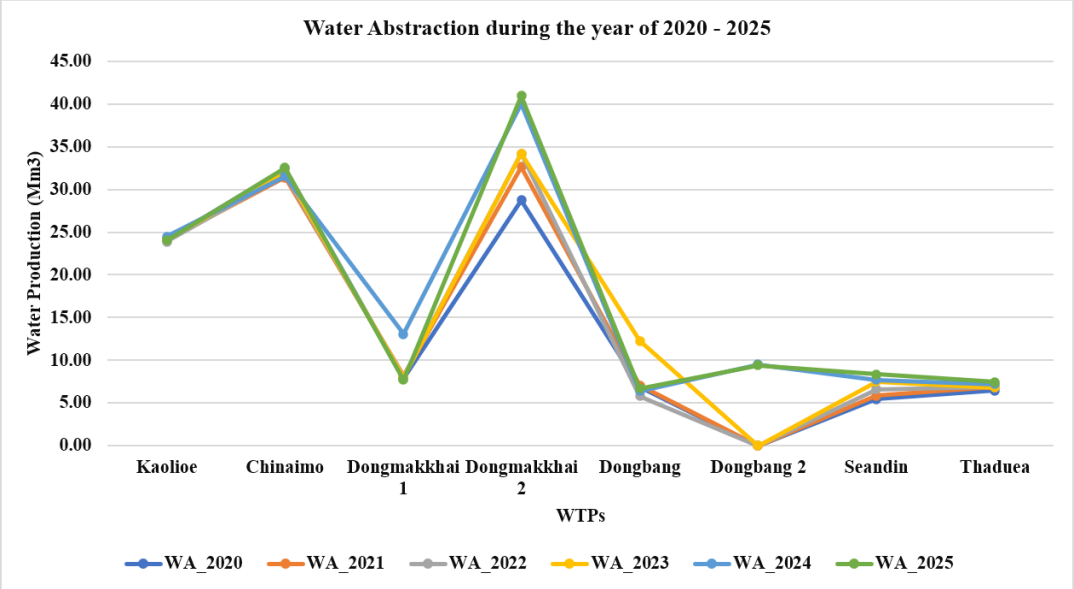

Fig. 2. Spatial-temporal trends of water abstraction across eight treatment plants in Vientiane Capital during 2020–2025, highlighting variations in production capacity.

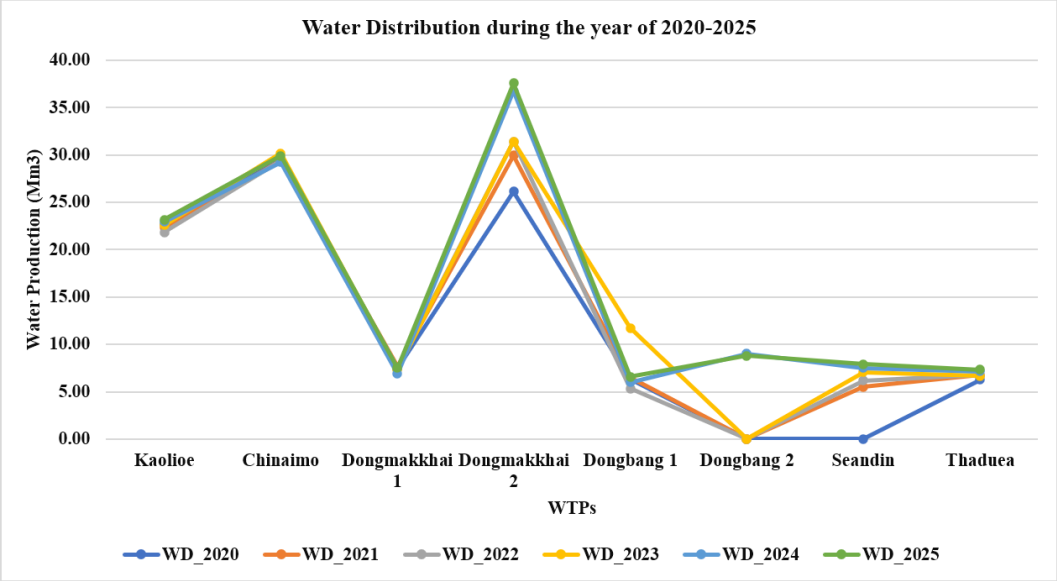

Fig. 3. Spatial-temporal trends of distribution across eight treatment plants in Vientiane Capital during 2020-2025, highlighting variations in supply capacity.

As shown in **Table 2**, the stagnant growth of the Chinaimo and Kaolieo facilities reflected in marginal CAGRs of +0.06% and -0.08% for abstraction, respectively indicates that the infrastructure serving the urban core has reached its operational capacity. The physical limits of their distribution networks cannot accommodate further peripheral expansion without inducing significant pressure losses across the grid.

4.1.2. The Northern Stratum and Strategic Spatial Relocation (The Dongmakkhai System)

To address the capacity limits of the central plants, NPNL shifted production capacity toward the north-northeast of the city. The development of the Dongmakkhai WTP complex was the main driver of this transition.

Dongmakkhai 1 exhibited relatively stable operations, with abstraction declining slightly from 7.85 Mm³ in 2020 to 7.71 Mm³ in 2025 (CAGR = -0.36%). Distribution volumes remained nearly constant, reaching 7.52 Mm³ in 2025 (CAGR = +0.11%).

Dongmakkhai 2 demonstrated rapid growth and emerged as the largest single water producer in Vientiane Capital by 2025. Abstraction increased from 28.73 Mm³ in 2020 to 40.96 Mm³ in 2025 (CAGR = +7.35%), while distribution rose from 26.12 Mm³ to 37.58 Mm³ (CAGR = +7.55%). The CAGR was calculated using the standard formula $\left(\frac{37.58}{26.12}\right)^{1/5} - 1$, confirming the strong upward trajectory. This expansion underscores the strategic role of Dongmakkhai 2 in meeting rising municipal demand. This spatial trend aligns with the city's demographic expansion.

The spatial intensity of water abstraction and distribution was further analyzed using KDE, as shown in **Fig. 4** and **Fig. 5**. These maps reveal the shifting operational focus from historical production nodes towards emerging high-density distribution zones, providing a clear visualization of the infrastructure expansion over the study period. The rapid growth of administrative, residential, and commercial hubs in the Xaythany and Saysettha districts has shifted the center of gravity for water demand away from the Mekong banks and toward the Nam Ngum River basin in the north-northeast.

Table 2.
Annual water abstraction and distribution volumes (Mm^3) across water treatment plants, 2020-2025.

WTP name	Metric Type	2020	2021	2022	2023	2024	2025	CAGR (%)
Kaolieo	Abstraction	24.15	24.11	23.86	24.15	24.49	24.05	-0.08
	Distribution	22.68	22.30	21.83	22.57	22.94	23.16	+0.42
Chinaimo	Abstraction	32.47	31.39	31.77	32.03	31.54	32.57	+0.06
	Distribution	29.46	29.37	29.44	30.19	29.23	29.92	+0.31
Dongmakkhai 1	Abstraction	7.85	8.13	8.07	8.00	13.05	7.71	-0.36
	Distribution	7.48	7.66	7.47	7.35	6.88	7.52	+0.11
Dongmakkhai 2	Abstraction	28.73	32.65	34.23	34.21	40.04	40.96	+7.35
	Distribution	26.12	29.93	31.40	31.39	36.74	37.58	+7.55
Dongbang 1	Abstraction	6.88	7.06	5.80	12.25	6.40	6.72	-0.47
	Distribution	6.35	6.49	5.35	11.73	6.01	6.58	+0.71
Dongbang 2	Abstraction	0.00	0.00	0.00	0.00	9.48	9.39	
	Distribution	0.00	0.00	0.00	0.00	9.02	8.81	
Seandin	Abstraction	5.45	5.85	6.60	7.47	7.68	8.33	+8.86
	Distribution	0.00	5.52	6.18	7.08	7.50	7.93	
Thaduea	Abstraction	6.46	6.87	6.85	6.77	7.19	7.42	
	Distribution	6.29	6.77	6.76	6.67	7.14	7.32	
Total abstraction (Mm^3)		111.99	116.06	117.18	124.88	139.87	137.15	+4.14
Total distribution (Mm^3)		98.38	108.04	108.43	116.98	125.46	128.82	+5.54
Abstraction-distribution gap (Mm^3)		13.61	8.02	8.75	7.90	14.41	8.33	
Distribution/abstraction ratio (%)		87.85	93.09	92.53	93.67	89.70	93.93	

Note: *Abstraction refers to the annual volume withdrawn or supplied to the treatment system. Distribution refers to the annual volume delivered to the distribution network. The abstraction-distribution gap is an operational indicator and should not be interpreted as Non-Revenue Water (NRW) without billing and authorized-consumption data. The Dongbang 2 abstraction volume for 2025 was corrected to 9.39 Mm³ after verification against the utility record.*

4.1.3. Peripheral Adaptation: The Dongbang Cluster and Secondary Nodes

The Dongbang 1 WTP displayed high variability, with abstraction peaking abnormally at 12.25 Mm³ in 2023 before returning to 6.72 Mm³ in 2025. Distribution volumes stabilized at 6.58 Mm³ in 2025 (CAGR = +0.71%). These fluctuations highlight the vulnerability of groundwater-dependent systems to seasonal dry spells and declining aquifer levels.

Dongbang 2 commenced operations in 2024 with abstraction of 9.48 Mm³ and distribution volume of 9.02 Mm³. In 2025, abstraction slightly decreased to 9.39 Mm³, while distribution remained relatively stable at 8.81 Mm³. These values reflect consistent operational performance, with the facility maintaining steady service output despite marginal variations in raw water intake.

Seandin showed consistent growth, with abstraction increasing from 5.45 Mm³ in 2020 to 8.33 Mm³ in 2025 (CAGR = +8.86%). Distribution began in 2021 at 5.52 Mm³ and expanded to 7.93 Mm³ by 2025, reflecting the successful integration of new infrastructure.

Thaduea maintained steady operations, with abstraction rising from 6.46 Mm³ to 7.42 Mm³ and distribution from 6.29 Mm³ to 7.32 Mm³ between 2020 and 2025. This underscores its role as a stable secondary supply node, contributing gradual growth rather than functioning solely as a booster facility.

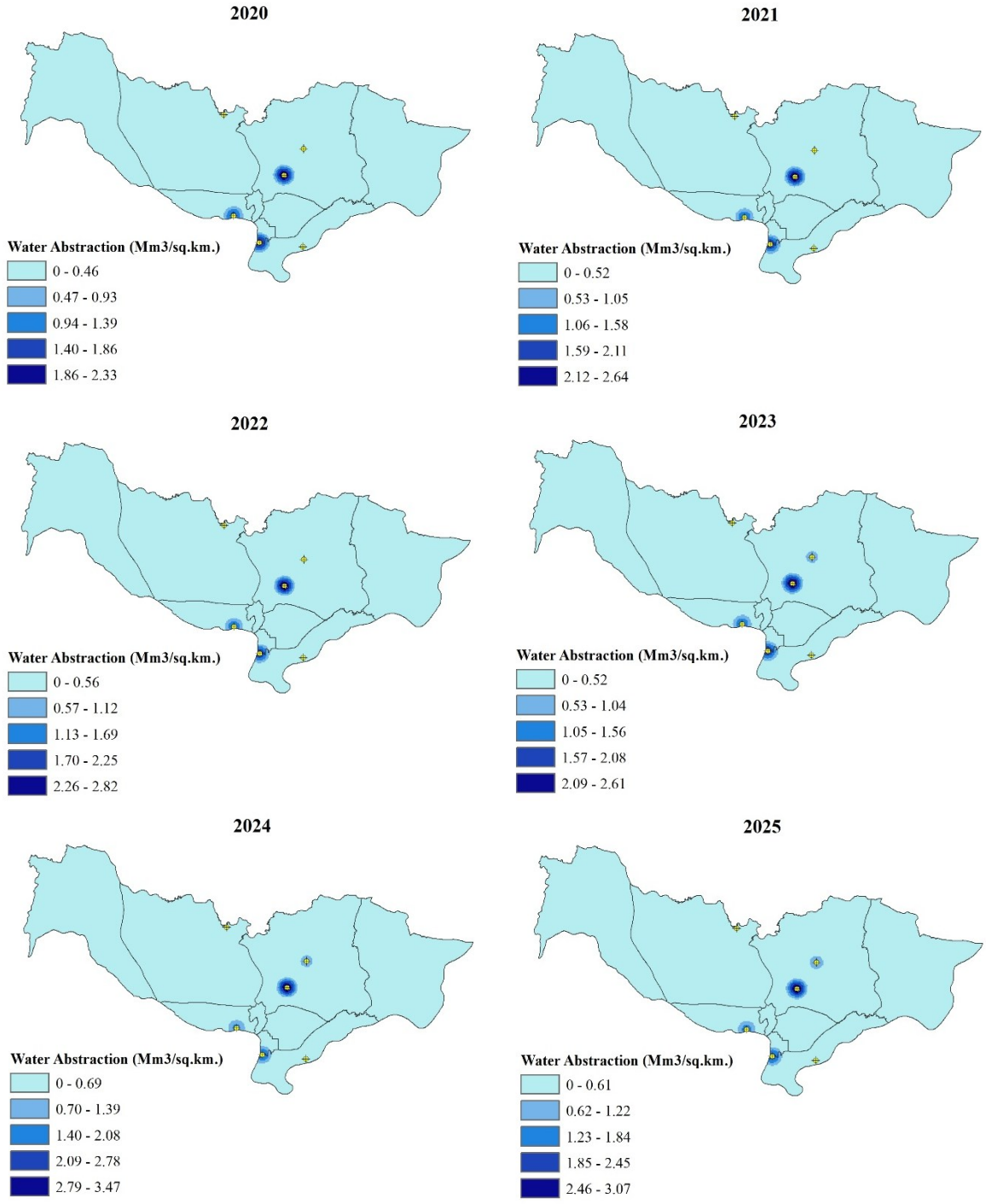

Fig. 4. Spatial-Temporal dynamics of water abstraction during 2020-2025.

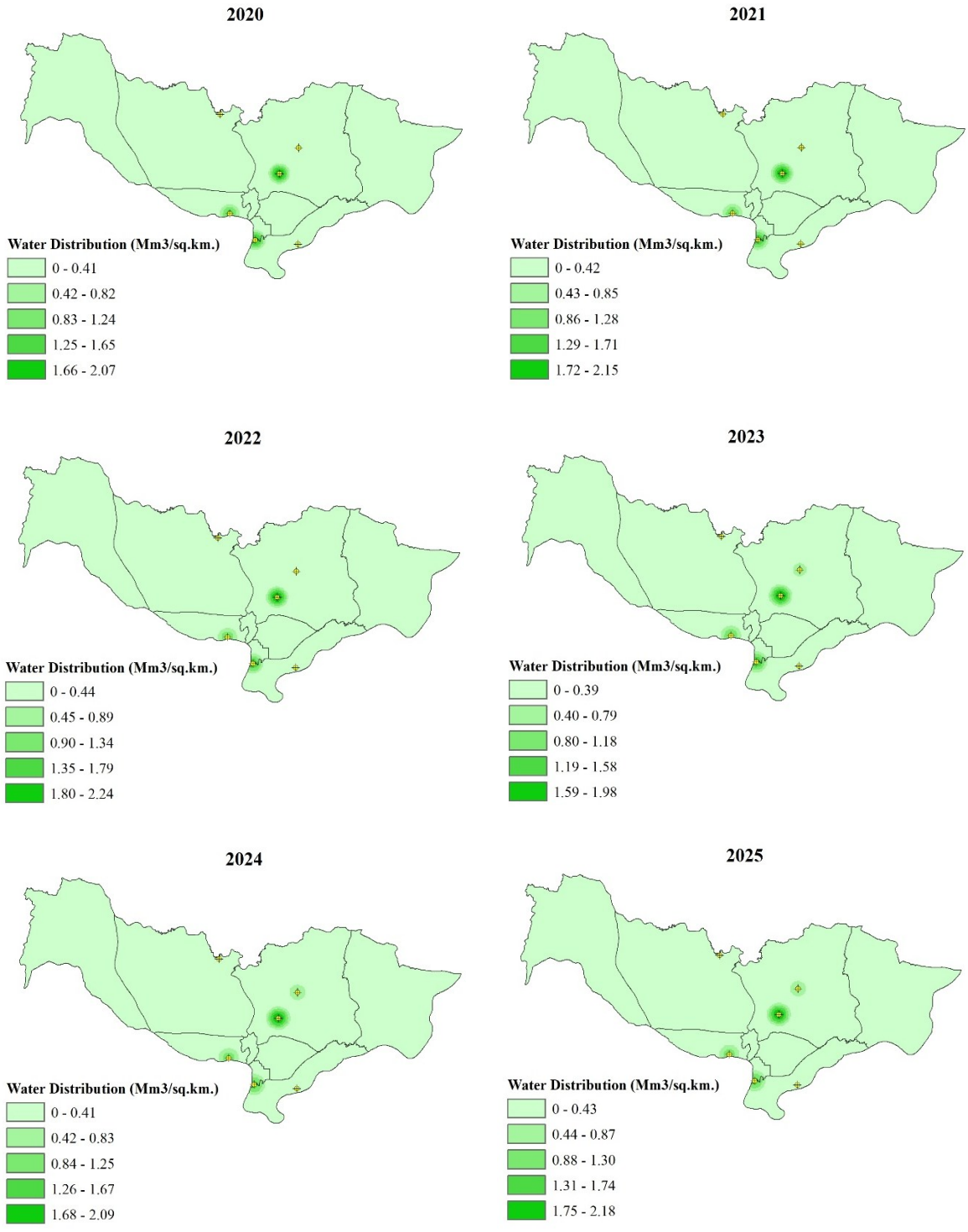

Fig. 5. Spatial-Temporal dynamics of water distribution during 2020-2025.

4.2. Diagnostic of System Efficiency and Operational Gaps in Municipal Infrastructure

Unaccounted-for water loss across the network raises issues regarding System Efficiency (SE_j), NRW, and pipeline friction (as shown in the diagnostic framework in **Fig. 6**)

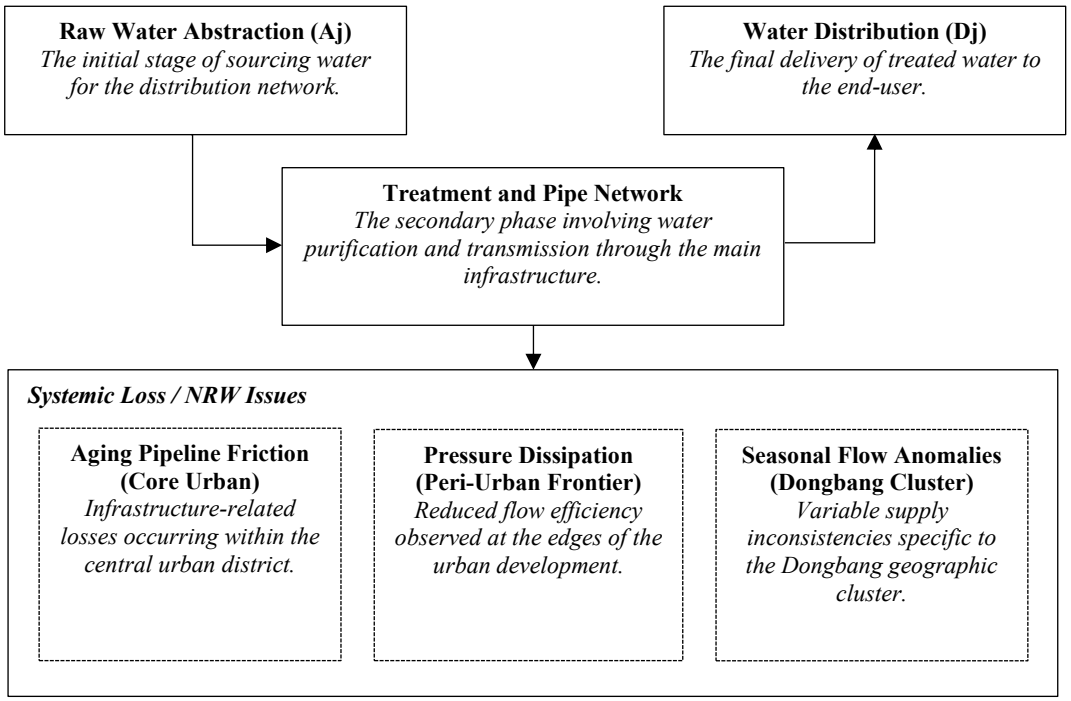

Fig. 6. The water distribution lifecycle and systemic losses.

4.2.1. Aging Infrastructure and Physical Losses in the Urban Core

In the oldest districts of the city, served by the Chinaimo and Kaolieo plants, the average SE_j ranges between 88% and 93%. The unaccounted-for physical loss of 7% to 12% is primarily due to, (a) physical leaks, blockages, and pipe bursts in old ductile iron and asbestos-cement pipelines and (b) filter backwashing and technical treatment processes within old physical structures.

4.2.2. Pressure Dissipation and Hydraulic Friction on the Urban Fringe

In contrast, while the newer Dongmakkhai 2 system maintains a high treatment plant efficiency (> 91.7%) it faces challenges in water delivery. Because Dongmakkhai 2 distributes water over long distances to supply the peri-urban fringe, it suffers from heavy hydraulic friction and pressure drop-offs. This explains why residents in outer districts report weak flow rates despite the plant's high production volumes.

4.2.3. Monitoring and Data-Logging Gaps

The lack of operational abstraction logs for the Thaduea node shows a gap in system telemetry. Historically, NPNL has prioritized expanding production capacity over installing digital monitoring networks and flow meters. This lack of real-time monitoring makes it difficult to track physical water losses across the metropolitan grid.

4.3. Socio-Spatial Determinants of Urban Water Demand and Consumer Perceptions

An analysis of the household survey data (N = 360) reveals how socio-demographic indicators relate to actual spatial water security on the ground.

4.3.1. Household Characteristics

The study included 360 surveyed households. Household size ranged from one to seven persons, with a mean of 3.56 persons per household. Most households reported monthly income between 5,000,001 and 10,000,000 Lao Kip. (**Table 3**).

Table 3.

Household Characteristics of Surveyed Households.

Variable	Category	n	%
Household size	Mean	3.56 persons	-
Household size	Range	1-7 persons	-
Monthly household income	<1,000,000 LAK	0	0.0
Monthly household income	1,000,000-2,500,000 LAK	0	0.0
Monthly household income	2,500,001-5,000,000 LAK	76	21.1
Monthly household income	5,000,001-10,000,000 LAK	192	53.3
Monthly household income	>10,000,000 LAK	92	25.6
Total		**360**	**100.0**

4.3.2. Water Sources and Household Access to Piped Water

Public piped water was selected by 320 households (88.9%), indicating that it was the dominant water source among respondents. Purchased drinking water was selected by 121 households (33.6%), while 12 households (3.3%) selected groundwater or wells. The use of purchased drinking water suggests that a substantial proportion of households may rely on supplementary sources for drinking purposes (**Table 4**). All surveyed households reported piped-water access. A total of 243 households (67.5%) had a piped connection inside the dwelling, while 117 households (32.5%) had a connection at the dwelling frontage.

Table 4.

Household water sources and piped-water access.

Variable	Category	n	%
Water sources selected	Public piped water	320	88.9
Water sources selected	Private/community piped water	28	7.8
Water sources selected	Groundwater/well	12	3.3
Water sources selected	Purchased drinking water	121	33.6
Piped-water access	Connection inside dwelling	243	67.5
Piped-water access	Connection at dwelling frontage	117	32.5

Note: Water-source responses were multiple-response selections; percentages do not sum to 100%.

4.3.3. Spatial Accessibility to Water Treatment Plants

The average Euclidean distance (**Table 5**) from surveyed households to the nearest WTP was 12.03 km. The nearest household was located 0.23 km from a WTP, whereas the farthest household was located 52.11 km away. A total of 236 households (65.6%) were located within 10 km of their nearest WTP.

Table 5.

Euclidean Distance from Surveyed Households to the Nearest Water Treatment Plant.

Distance to nearest WTP	n	%
< 5 km	92	25.6
5 - < 10 km	144	40.0
10 - < 20 km	52	14.4
20 - < 40 km	63	17.5
≥ 40 km	9	2.5
Total	**360**	**100.0**

Distance summary: mean = 12.03 km; minimum = 0.23 km; maximum = 52.11 km.

4.3.4. Service Conditions and Reported Problems

Most households (77.8%) reported water availability throughout 24 hours (**Table 6**). However, 22.2% reported that water was not continuously available. Perceived water quality was generally positive for domestic use, but only 10.6% considered the water suitable for direct drinking without filtration. More than half of respondents (55.0%) reported that water quality was good but required filtration before drinking.

Low water pressure was the most frequently reported service problem, affecting 67.2% of households. Water shortages were reported by 44.4% of households, and water-quality problems were reported by 32.8%.

Table 6.

Water-service conditions and reported problems.

Indicator	Category	n	%
Service continuity	Water available 24 hours/day	280	77.8
Service continuity	Water not available 24 hours/day	80	22.2
Perceived water quality	Very good; suitable for direct drinking	38	10.6
Perceived water quality	Good; filtration required before drinking	198	55.0
Perceived water quality	Moderate; domestic use only	124	34.4
Reported problem	Water-quality problem	118	32.8
Reported problem	Water shortage	160	44.4
Reported problem	Low water pressure	242	67.2

4.3.5. Satisfaction, Improvement Priorities, and Willingness to Pay

Overall satisfaction with piped-water services was generally positive. A total of 68 households (18.9%) were very satisfied, and 227 households (63.1%) were satisfied. Together, these groups represented 81.9% of surveyed households. However, 23 households (6.4%) were moderately satisfied and 42 households (11.7%) were slightly satisfied. The most commonly identified improvement priority was increased water pressure, selected by 322 households (89.4%). This was followed by increased water quantity (56.9%), continuous 24-hour supply (23.3%), improved water quality (22.2%), and expanded service coverage (22.2%).

Regarding willingness to pay, 202 households (56.1%) were willing to pay an additional 50,000 Lao Kip per month for service improvements, while 38 households (10.6%) were willing to pay an additional 100,000 Lao Kip per month. One-third of households were not willing to pay additional charges (**Table 7**).

Table 7.

Satisfaction, Improvement Priorities, and Willingness to Pay.

Indicator	Category	n	%
Overall satisfaction	Very satisfied	68	18.9
Overall satisfaction	Satisfied	227	63.1
Overall satisfaction	Moderate satisfied	23	6.4
Overall satisfaction	Slightly satisfied	42	11.7
Overall satisfaction	Not satisfied	0	0.0
Improvement priority	Increase water quantity	205	56.9
Improvement priority	Improve water quality	80	22.2
Improvement priority	Increase water pressure	322	89.4
Improvement priority	Ensure 24-hour supply	84	23.3
Improvement priority	Expand service area	80	22.2
Willingness to pay	No additional payment	120	33.3
Willingness to pay	Additional 50,000 LAK/month	202	56.1
Willingness to pay	Additional 100,000 LAK/month	38	10.6

5. DISCUSSION

The expansion of Vientiane Capital's water infrastructure, marked by the strategic transition from Mekong-based extraction (Kaolieo and Chinaimo) to inland river systems in the northeast (Dongmakkhai 2), reflects the city's response to rapid horizontal urban growth. As shown by Nakamura (2019) and Gumma et al. (2023), residential developments are moving away from the historic city center along the Mekong River toward peripheral zones. While this spatial restructuring has successfully increased total municipal production capacity, the findings of this study demonstrate that increasing output volume does not inherently guarantee equitable access or reliable service at the household level.

Despite the widespread physical reach of the piped-water network evidenced by 88.9% of households selecting public piped water and 100% reporting some form of connection service reliability remains a significant challenge. The discrepancy between broad infrastructure coverage and the reported experience of 67.2% of households facing low water pressure, alongside 44.4% experiencing shortages, highlights a critical mismatch between supply-side production capacity and distribution-network hydraulic performance. This suggests that the distribution network in Vientiane Capital may be experiencing significant hydraulic friction, pressure drops in peripheral zones, and systemic inefficiencies, which are typical of rapidly expanding urban networks in Southeast Asia where pipe networks often struggle to maintain pressure across long transmission distances (World Bank, 2020).

Spatial accessibility analysis further elucidates this challenge. With a mean household distance of 12.03 km to the nearest WTP, and one-fifth of the sampled households situated at least 20 km away, the geographic distance to treatment infrastructure is a significant spatial constraint. While physical distance alone does not determine hydraulic pressure, it is a primary indicator of network complexity. The spatial concentration of households reporting low pressure likely correlates with these more remote peripheral nodes, where lower network density and aging infrastructure hinder consistent delivery. This confirms that high plant-level production efficiency (e.g., at Dongmakkhai 2) is insufficient to ensure reliable service without local booster stations, pressure management systems, and proactive network rehabilitation.

Consumer perceptions of water quality and service reliability offer additional insights into the "hidden" gaps of the municipal system. Although 81.9% of surveyed households expressed overall satisfaction, a significant minority of 18.1% reported moderate or slight satisfaction.

Moreover, the reliance of 33.6% of households on purchased drinking water and 55.0% on household-level filtration suggests that, while the municipal supply is considered acceptable for domestic use, it does not currently command universal confidence for direct consumption. This indicates that improving drinking-water quality communication, water-quality monitoring, and service transparency are as important as pressure management for improving public satisfaction. The findings carry significant policy implications:

1) Infrastructure and Pressure Management: Capital investments should shift focus from sole production expansion to the construction of localized booster stations and secondary network optimization, particularly in the peri-urban areas of Xaythany and Saysettha to mitigate pressure drops.
2) Operational Monitoring and Asset Management: The abstraction–distribution gaps identified in this study highlight the need for a comprehensive utility water balance. NPNL should prioritize district-metered areas (DMAs) and systematic leakage detection to better understand where production losses occur.
3) Tariff and Service Reform: The high willingness to pay for improved service (66.7% of households) indicates public receptivity to tariff adjustments, provided they are accompanied by verified and visible gains in reliability, continuity, and pressure stability.
4) Integration of Evidence-Based Planning: Municipal planning should increasingly integrate utility production statistics with spatially referenced household survey data. By mapping areas where service problems (e.g., low pressure) cluster, the utility can better target infrastructure upgrades and improve resource allocation.

The study has limitations. It relied on cross-sectional survey data and Euclidean distance as a proxy for spatial accessibility, which does not account for the complexities of hydraulic distance, elevation, or specific supply-zone assignment. Future research should utilize network-based distance modeling, laboratory-measured water quality, and high-resolution pressure data to further refine the assessment of service reliability and spatial inequity. Nevertheless, this integrated analysis provides a robust diagnostic framework that links supply-side production data with demand-side household evidence, offering a valuable foundation for advancing sustainable urban water management in alignment with SDG 6.

6. CONCLUSIONS

This study provided a comprehensive assessment of municipal water-supply performance in Vientiane Capital by integrating operational records from eight WTPs (2020-2025) with structured survey data from 360 geographically referenced households. The supply-side analysis revealed that while total annual water abstraction increased from 111.99 Mm^3 in 2020 to 137.15 Mm^3 in 2025 (CAGR 4.14%), the expansion was driven primarily by newer facilities, particularly Dongmakkhai 2, which accounted for approximately 29.2% of total municipal water distribution in 2025.

Despite the expanded production capacity and widespread physical access with 88.9% of households using public piped water as their main source and 100% reporting a piped-water connection service reliability remains a critical concern. Household evidence revealed that 67.2% of respondents had experienced low water pressure, 44.4% reported shortages, and nearly 90% identified increased pressure as the primary priority for service improvement. These findings indicate that while Vientiane Capital has made significant progress in extending infrastructure coverage, the system currently faces substantial challenges in ensuring hydraulic adequacy and service reliability across the distribution network.

Geospatial analysis further contextualized these challenges, showing that the mean distance from surveyed households to the nearest WTP was 12.03 km, with 20% of households located at least 20 km away. While overall household satisfaction was predominantly positive (81.9% satisfied or very satisfied), the 18.1% of respondents reporting moderate satisfaction or dissatisfaction, coupled with widespread reports of low pressure, suggests that physical proximity to treatment infrastructure is not the sole determinant of service quality. Service experiences are likely mediated by network configuration, pipe condition, elevation, and localized pressure-management constraints.

The findings highlight that future urban water management in Vientiane Capital must shift from a singular focus on production expansion to a more integrated management approach. Priority should be given to improving pressure management, conducting systematic leakage detection, rehabilitating deteriorated distribution pipes, and establishing district-metered areas to better manage abstraction–distribution gaps. Furthermore, the willingness of most households to pay for service improvements suggests that tariff reforms, if clearly linked to verifiable gains in service reliability, could provide the necessary funding for these infrastructure upgrades.

This study provides a holistic diagnostic framework by linking utility production data with household-level spatial evidence. Future research should deepen this integration by merging verified geographic coordinates with distribution-network hydraulic models, laboratory-measured water quality, and long-term water-balance data. Such an approach will enable more robust spatial modelling of service inequalities and support targeted interventions essential for improving reliability, equity, and sustainability in alignment with Sustainable Development Goal 6.

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