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USER REQUIREMENTS FOR DEVELOPING A DATA VISUALIZATION MODEL TOWARD IMPROVING WATER DISTRIBUTION MANAGEMENT IN NAIROBI METROPOLITAN AREA, KENYA

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Abstract

Effective water distribution management relies on accurate data collection to maximize efficiency in operations and decision-making. In Kenya, most water service providers primarily engage in passive data collection, aiming to fulfill regulatory requirements set by the Water Services Regulatory Board (WASREB). This means that they do not fully utilize the collected data for insight extraction and improvement in water distribution management. This study aimed to bridge the gap by identifying user requirements for developing data visualization models in water distribution management. This enabled the design of a conceptual model for water distribution management. Enhancing water distribution through effective data visualization aligns with Sustainable Development Goals (SDGs) 6 and 11, focusing on clean water access and building resilient and sustainable urban infrastructure. A survey research design was applied, collecting data from 44 purposively sampled personnel from 11 selected water service providers within the Nairobi Metropolitan Area. The data was collected through the use of structured questionnaires. The data obtained was analyzed using Python with libraries such as Pandas for data cleaning as well as data manipulation, Matplotlib and Seaborn for data visualization. The results indicated that a majority of Water Service Providers are in a transitional phase, combining human oversight with the increasing adoption of automated monitoring solutions. Billing efficiency and billed volume are monitored most regularly, while non-revenue water and leak detection remain inadequately covered, creating operational blind spots. Respondents emphasized the need for a simple, role-based dashboard interface with configurable views, mobile access, as well as clear, intuitive visual indicators. Through these findings, the study proposes a set of visualization principles and functional requirements for developing a data visualization model for water distribution management. The study contributes to real-world implementations by providing a foundation for developing visualization models for enhancing efficiency, transparency, and resource utilization in water service companies.

Keywords: *Data Visualization, Model, Water Distribution, Visualization Tools, Water Service Providers*

Introduction

Access to clean water and a stable supply of water are a human right and a cornerstone of urban sustainability. Clean water supply in most of those rapidly growing urban areas, more so in developing countries, is threatened by numerous factors, including increasing demand, climate instability, aging infrastructure, as well as ineffective water management mechanisms (Chunyang et al., 2021). Nairobi Metropolitan Area in Kenya, having a rapidly growing populace of nearly 5 million people, exemplifies such dilemmas (Namsip, 2023).

Water demand in most regions exceeds supply, and a significant portion of the water is wasted through leaks, theft, and inadequate monitoring (AbuEltayef et al., 2023). Despite regulatory frameworks like the

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Water Regulation Information System (WARIS), which are enforced by Water Services Regulatory Board (WASREB), water service providers (WSPs) operating in the Nairobi Metropolitan Area are still grappling with effective management of water distribution, reasons being largely attributed to reliance on conventional, passive methods of data acquisition and reporting (WASREB, 2023).

Data-driven decision-making has been identified as a key enabler of operational effectiveness across many industries, and water utilities are no different (Andrienko et al., 2020). Strategic data utilization has the ability to maximize resource utilization, forecast demand behaviors, identify distribution inefficiencies, and inform maintenance activities (Oladipupo et.al, 2019). Data analysis-enabled water distribution systems can lower operational expenses, improve service delivery, and increase system resilience (Grigg, 2024; Gupta & Pandey, 2019).

Nonetheless, despite widespread data gathering by Kenya's WSPs, its application in decision-making remains very limited. This can be seen in the little use of data visualization tools, which are able to take raw data and make it usable by decision-makers. Kenyan WSPs continue to depend on static, periodic reporting tools and have not invested much in real-time monitoring as well as predictive analysis(WASREB, 2023). It follows that water distribution system management is still reactive, failing to capitalize on opportunities to utilize data to manage proactively (Chunyang et al., 2021). According to the United Nations' Sustainable Development Goals, which stress SDG 6 on clean water and sanitation as well as SDG 11 on sustainable cities and communities, there has been heightened awareness of the need for water management systems to be resilient. Implementation of these goals needs to incorporate innovation in technology and processes enhancing water governance mechanisms(Küfeoğlu, 2022; Schunke et al., 2014).

In the quickly evolving field of data mining, it is critical to efficiently extract meaningful insights from huge data sets (Ranjitha Bai A et al., 2024). In order to extract patterns, trends, and insights from huge datasets, data mining processes require the use of data analytics and visualization (Andrienko et al., 2020; Fry, 2008; Ranjitha Bai A et al., 2024). Across the world, numerous case studies have demonstrated the valuable benefits of data visualization in utility management. For example, California has its Water Evaluation and Planning system, an interactive platform through which stakeholders can view water distribution throughout the basin, analyze the impacts of different policy choices on water distribution, and make informed, knowledge-based decisions regarding water resource management (SEI, 2016).

Although data visualization tools have considerable potential to transform the way utility management is conducted, their use in Kenyan water service providers is minimal and often not customized (Qin et al., 2020). The existing literature on water distribution in Sub-Saharan Africa has focused on infrastructural and governance issues; however, there is a lack of empirical research on how data visualization can be systematically incorporated into operational decision-making. Thus, the Kenyan management of water distribution remains limited to static, reactive reporting, rather than proactive, data-driven reporting (Ngueyim Nono et al., 2024; WASREB, 2023).

The gap highlights the importance of visualization models that are not only technically sound but also responsive to the specific realities of operating Kenyan WSPs, which are constrained by limited infrastructure, data quality, and staff capacity. Although world examples of the interactive, real-time monitoring systems, like the case of WEAP in California and SABESP in Brazil, demonstrate their effectiveness, local applications of this kind are underutilized in Kenya (O'Connor et al., 2023; SEI, 2016). To fill this gap, the paper examines the existing data practices in WSPs in the Nairobi Metropolitan Area, with the objective of determining user needs in an effective data visualization model. By doing so, it provides a context-specific framework that can improve operational performance,

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transparency, and resource efficiency in the Kenyan water sector.

Research Methodology

To identify user requirements in the development of a data visualization model in water distribution management, this study used a cross-sectional survey design. The design was suited as the objective was to provide a snapshot of the practices, needs, and preferences of water service providers (WSPs) at a particular point in time. This approach aligns with requirements elicitation studies in ICT and information systems, where the initial stage involves understanding user perspectives and contextual challenges before model or system development (Batra & Bhatnagar, 2019).

The target population for this study consisted of members of the management bodies of the selected 11 WSPs within the Nairobi Metropolitan Area. These members were responsible for managing data handling and water distribution, and were involved in data reporting, analysis, or decision-making processes. The targeted staff were managers, engineers, and the technical staff tasked with monitoring the metrics of the distribution of water, informing the regulatory agencies, and taking operating decisions. This ensured that the survey gathered knowledge and perspectives from the staff with first-hand experience in operating and managing the distribution of water and decision-making using data. Table 1 shows the distribution of the sample across the 11 selected WSPs.

Table 1

Distribution of sample by water company and management members

Water Company	No. of Mgt Members	Selected Sample
Nairobi City	12	4
Runda	7	4
Tatu City	6	4
Two Rivers	6	4
Ruiru-Juja	9	4
Limuru	7	4
Kikuyu	7	4
Thika	9	4
Kiambu	9	4
Mavoko	8	4
Oloolaiser	8	4
Total	87	44

Purposive sampling was employed to select the respondents. It was appropriate because only the managers actively engaged in decision-making and management of the water distribution were targeted. The small- and large-scale WSPs were selected to obtain diverse views on different service provider needs and obstacles. Stratified Sampling was also used, and the 11 selected companies were the basis of creating the different strata, where each company was a Stratum, and a purposive sample of 4 participants was selected. Therefore, a total of 44 participants, four from each of the 11 WSPs, were involved in the study. The 11 WSPs were selected based on their proximity to the capital city of Kenya, Nairobi. This ensured we targeted the most Urban settings within the Metropolitan Region.

The data were gathered through a structured survey questionnaire aimed at collecting information on data usage practices, operational processes, and visualization requirements among water service providers. The questionnaire included combinations of closed-ended items such as the use of the Likert

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scale and multiple-choice questions. These were employed to collect quantitative data on the frequency of data gathering, the data visualization tools in actual use, as well as the views of the respondents regarding the effectiveness of the data visualization tools. The questionnaire further included questions to determine the WSPs' specific data visualization requirements, including interactive dashboard preferences, geospatial mapping, and historical trend analysis.

Both online and face-to-face surveys were conducted, subject to the respondents' discretion. The questionnaire was issued to the selected staff once their informed consent was secured. The response rate was 100%, as all 44 respondents answered the questionnaire. The data gathering was conducted within a four-week timeframe.

After all the 44 survey responses had been obtained, data was prepared systematically and started with cleaning and validation using Microsoft Excel. The preliminary steps included locating and treating missing values, identifying outliers, and conducting internal consistency checks to ensure the dataset was complete, precise, and ready for analysis. After it was cleaned, the data were imported into Microsoft Power BI to be further processed and visualized. In the built-in Python scripting activity in Power BI, Pandas, a popular Python package for data manipulation, was utilized to perform analytical procedures. Descriptive statistics, including frequencies and percentages, were employed to summarize responses and identify user requirements by highlighting common practices, priorities, and preferences among water service providers in relation to data visualization needs. In order to supplement the results of the statistical output, graphic representations were created with the aid of Matplotlib and Seaborn, which were performed in Power BI. The interactive visual effects, such as bar charts, pie charts, and heatmaps, have been produced by these scripts.

The use of the Excel data-cleaning framework, the Python and production server tools, and the Power BI visualization capabilities produced by the study a powerful and efficient analysis process. Repeatability of code and interactiveness of the produced visual dashboards also played an important role in gathering insights into user needs and shaped the future development of the proposed data visualization model to enhance the management of water distribution.

Ethical standards rank high in ensuring integrity, transparency, and respect for participants' rights in this data visualization research on water management. These standards were ensured by obtaining the proper research permits and ethical clearance from the National Commission for Science, Technology, and Innovation (NACOSTI) initially. The participants were given clear and complete information regarding the aim, objective, and scope of the research. The participants were assured autonomy, freedom to withdraw from the research at any moment without punishment. Anonymity during data collection was assured, where all the responses were handled ethically and solely for the proposed objective of carrying out this piece of work.

Results and Discussions

Water Distribution Monitoring Methods

The survey revealed that a majority of water service providers (68.2%) employed a mixed-method approach to monitor their distribution networks, integrating both automated sensor data and manual field inspections as shown in Figure 1 below. A further 20.5% of respondents reported relying exclusively on fully automated systems, demonstrating growing adoption of digital monitoring technologies. The remaining 11.4% continued to use solely manual methods, which may limit their ability to detect and respond to distribution anomalies in real time.

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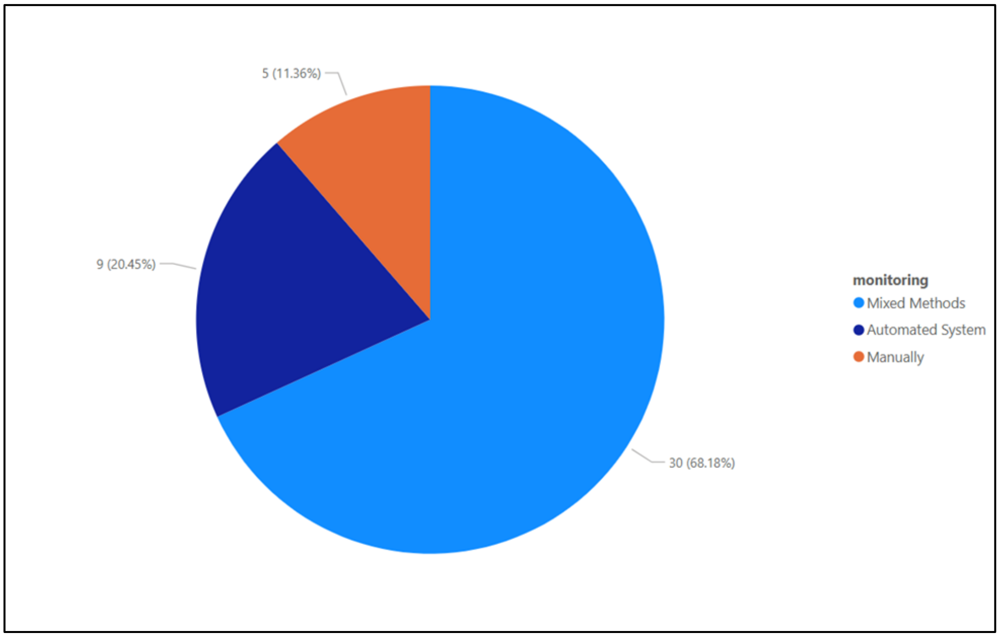
Figure 1

Monitoring methods for the Water Distribution Data



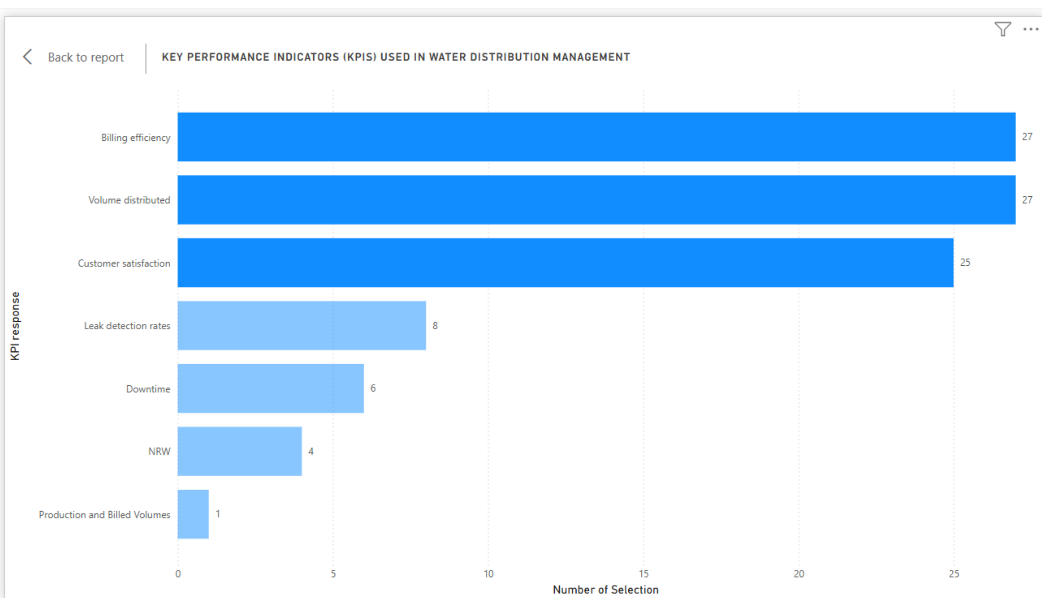
These results presented in Figure 1 above underscore a transitional phase in monitoring practices, where organizations seek to balance technological investments with established manual oversight.

Key Performance Indicators for Efficiency

Figure 2 show the distribution of KPIs when Respondents were asked to select all performance metrics they regularly track.

Figure 2

KPIs for monitoring efficiency



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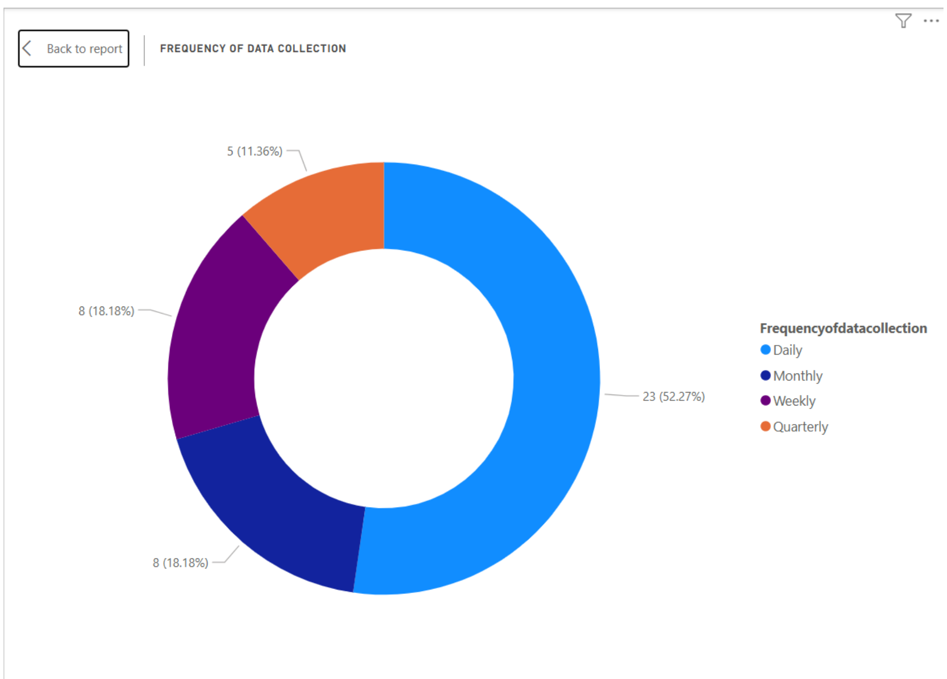
Billing efficiency and volume distributed were each chosen 27 times, translating to more than 50% of all selections, making them the most frequently monitored indicators. Customer satisfaction followed closely with 25 selections, reflecting an emphasis on service quality. In contrast, infrastructure-focused metrics such as leak detection rates (8 selections) and non-revenue water (NRW) (4 selections) were far less commonly tracked. The relatively low prioritization of NRW, a critical measure of system loss, suggests an opportunity for improved visibility into water loss management through targeted visualization tools. As shown in Figure 2, the dominance of financial indicators over loss-related metrics underscores an imbalance in current monitoring practices that visualization models could help address.

Frequency of Data Updates

Figure 3 presents the frequency at which Water Service Providers (WSPs) update their distribution data, reflecting how often operational insights are refreshed for decision-making.

Figure 3

Data Update Frequency



When questioned about the frequency at which distribution data are updated, 52.3% reported updating daily, reflecting the strong desire to conduct near-real-time monitoring. Weekly and monthly update frequencies were reported by 18.2% of WSPs, respectively, indicating that there is still an acceptance of periodic reporting for trend analysis and planning in certain circumstances. A mere 11.4% updated on a quarterly schedule. The large majority of daily updates reflect the demand for timely data, which needs to be met by visualization models to facilitate immediate decision-making. As illustrated in Figure 3 above, the predominance of daily updates emphasizes a growing expectation for visualization systems that can process and display information in real time.

Challenges in Distribution Management

Figure 4 illustrates the primary challenges identified by Water Service Providers (WSPs) in managing water distribution systems, as reported through multiple-choice responses. Monitoring and reporting led the list with 27 citations, referring to the problems of data gathering and transparency.

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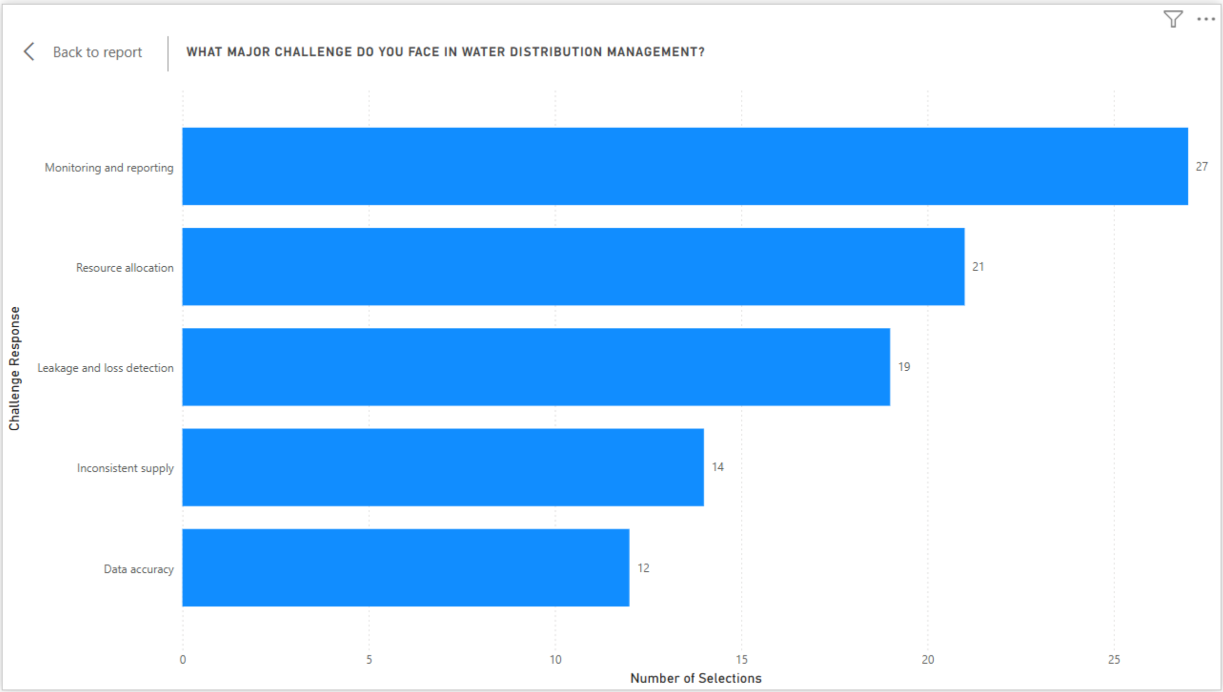
Figure 4

Major Challenges faced by WSPs



Issues of resource allocation were cited 21 times, pointing to the inequitable and wasteful distribution of human and financial resources. Leakage detection was found to be a major problem (19 citations), underscoring the necessity of instruments that can detect losses timely. Other significant problems were found to be inconsistent supply (14 citations) and data accuracy 12 citations). As shown in Figure 4, the prominence of monitoring, reporting, and resource allocation challenges highlights the need for visualization models that can enhance transparency, optimize resources, and strengthen operational accountability.

Preferred Data Sources

Figure 5 presents the distribution of preferred data sources identified by respondents as most critical for effective water distribution visualization. The results suggest that billing data (29 selections) and Production Data (25 selections) are most often collected, which aligns with the strong value placed on financial monitoring and operational effectiveness. This implies that up to 52% of all the respondents find Billing and Production Data essential to interpreting system performance, determining revenue streams, and supporting the financial viability of WSPs. Customer Usage Data (19 selections) and Historical Data (16 selections) rank next, as respondents consider these to be useful decision-supporting inputs.

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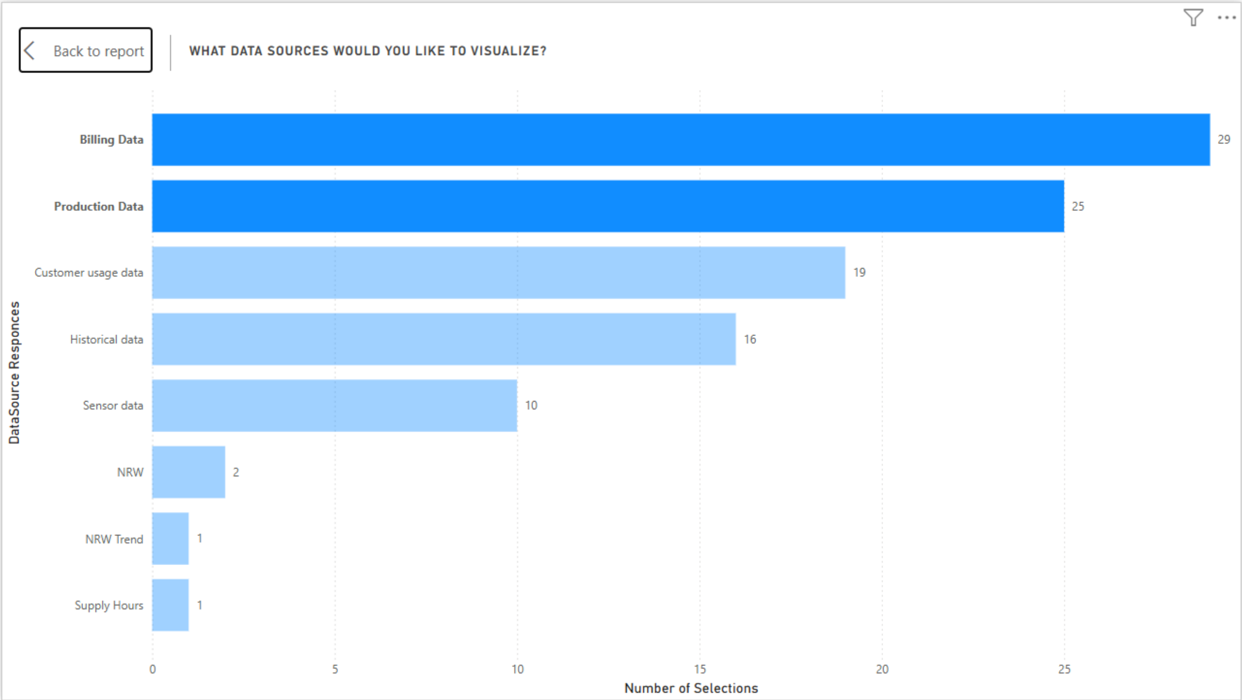
Figure 5

Preferred Data Sources for Visualization



These data are useful in demand forecasting and understanding consumer trends, both of which are essential for maximizing water distribution. These findings suggest that an optimal data visualization model for managing the water distribution system must preferentially include the combination of financial, operational, and customer usage data with the incorporation of real-time sensor data for ongoing system monitoring. Future models may also be improved with the increased focus on monitoring loss of water and optimizing the effectiveness of the system for distributing the water.

Top Visualization Features Desired

Figure 6 illustrates the visualization features most preferred by respondents, reflecting the functional priorities that should guide the design of an effective water distribution dashboard.

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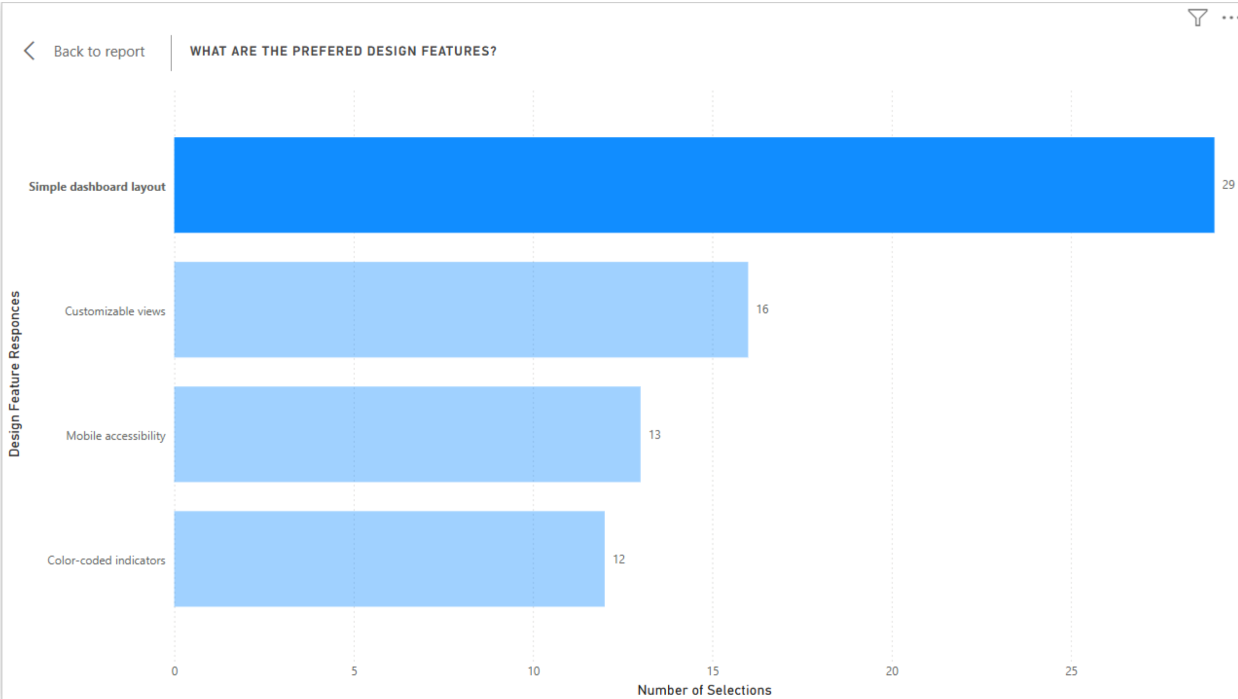
Figure 6

Most preferred Visualization Features



A simple dashboard design was the most popular response, with 29 answers citing the requirement for an interface that provides key metrics on demand, minimizes mental load, and enables fast operational evaluation. Following that, customizable views were cited in 16 answers, illustrating the appeal of tailoring data displays to specific users' roles—whether to track financial performance, distribution effectiveness, or customer trends. Mobility was another key priority (13 responses), highlighting the allowance for real-time, on-the-move monitoring for both decision-makers and field staff. Lastly, 12 participants rated color-coded indicators as top priority, highlighting the role of clear visual signals such as green for normal, amber as warning, and red as critical in enabling fast and accurate decision-making. These findings imply a model of visualization that is centered on simplicity, flexibility, access remoteness, and immediacy of interpretation.

Having already defined the general design characteristics which users consider vital in a visualization model, the research had gone ahead to test the particular operational and managerial features which practitioners would give priority in a dashboard setup. To capture these preferences, respondents were asked about what they would like to see represented at the core. The resulting area chart illustrates the distribution of these priorities across various professional functions, providing a more detailed insight into the constitutive components that must form the basis of an effective water distribution visualization model. Figure 7 presents the visualization preferences across different professional groups, highlighting how user priorities vary depending on their operational and managerial roles within the water distribution sector.

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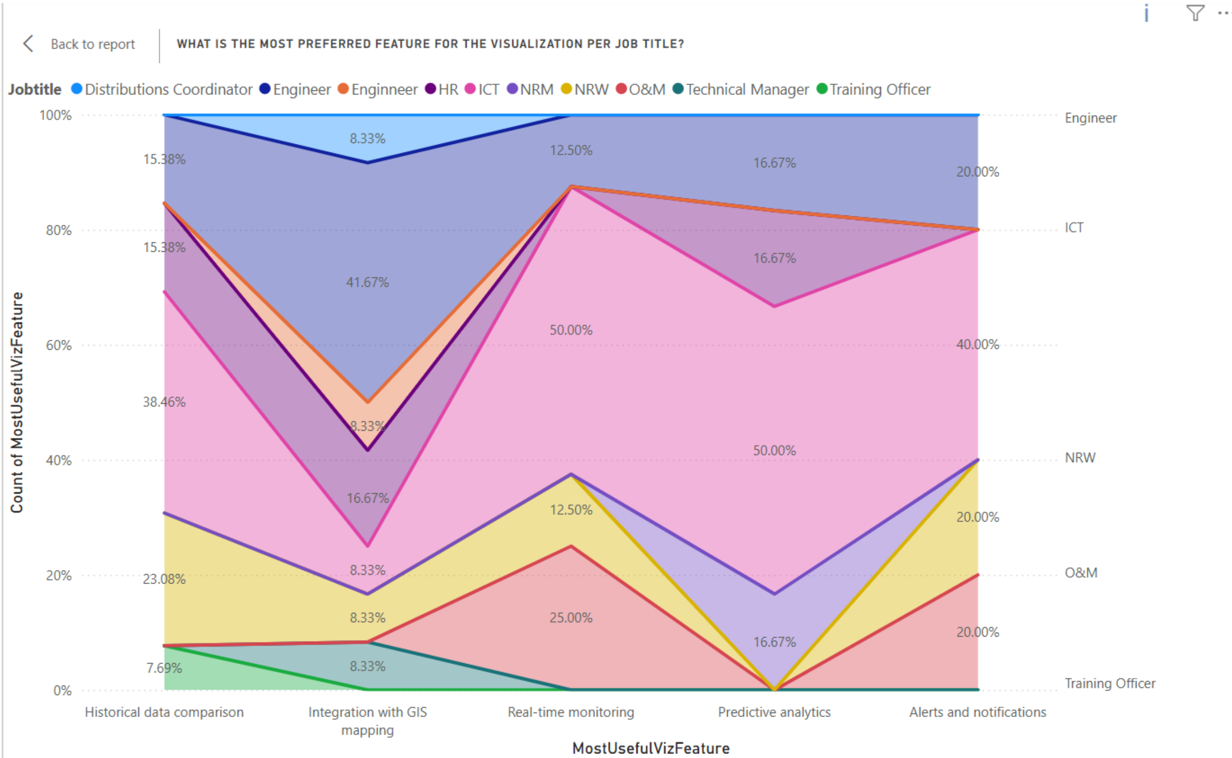
Figure 7

Visualization Preferences across Different Job Groups



Although historical data comparison was chosen by the largest percentage of respondents, it was not equally emphasized. This functionality was rated highest by ICT officers (38%), NRW (23%), and engineers (15%), indicating that trend analysis is especially relevant to technically oriented jobs, which depend on performance tracking.

A similar trend was observed in incorporation of GIS mapping, which was the most appreciated by engineers(42%), HR(17%) and NRW Specialist(9%). This indicates the extreme importance of spatial analysis in facilitating activities like system monitoring, leak detection and resource allocation. The respondents in operations and maintenance positions highly valued real-time monitoring by asserting the importance of tools capable of assisting them in monitoring constant processes of distribution.

Overall, Figure 7 shows that whereas historical trend comparison, the integration of GIS, and actual monitoring remain the fundamental priorities of all job functions, certain preferences are role specific and, therefore, require the use of a role-sensitive visualization model that would adjust its capabilities to the operational and managerial needs of various user groups.

Professional Experience and Satisfaction Levels

Figure 8 illustrates the relationship between satisfaction with the current data visualization practice and familiarity with Data Visualization tools at various levels of experience. Its results suggest that the satisfaction with current visualization approaches decreases with a lack of experience. Individuals with five or more years of experience are the most satisfied, indicating that they have learned to effectively utilize or maximize the benefits of traditional visualization methods. Nevertheless, those with less than one year of experience show the lowest level of satisfaction, which may indicate that they are dissatisfied with outdated or inefficient visualization practices that do not meet current expectations. Conversely, the level of familiarity with

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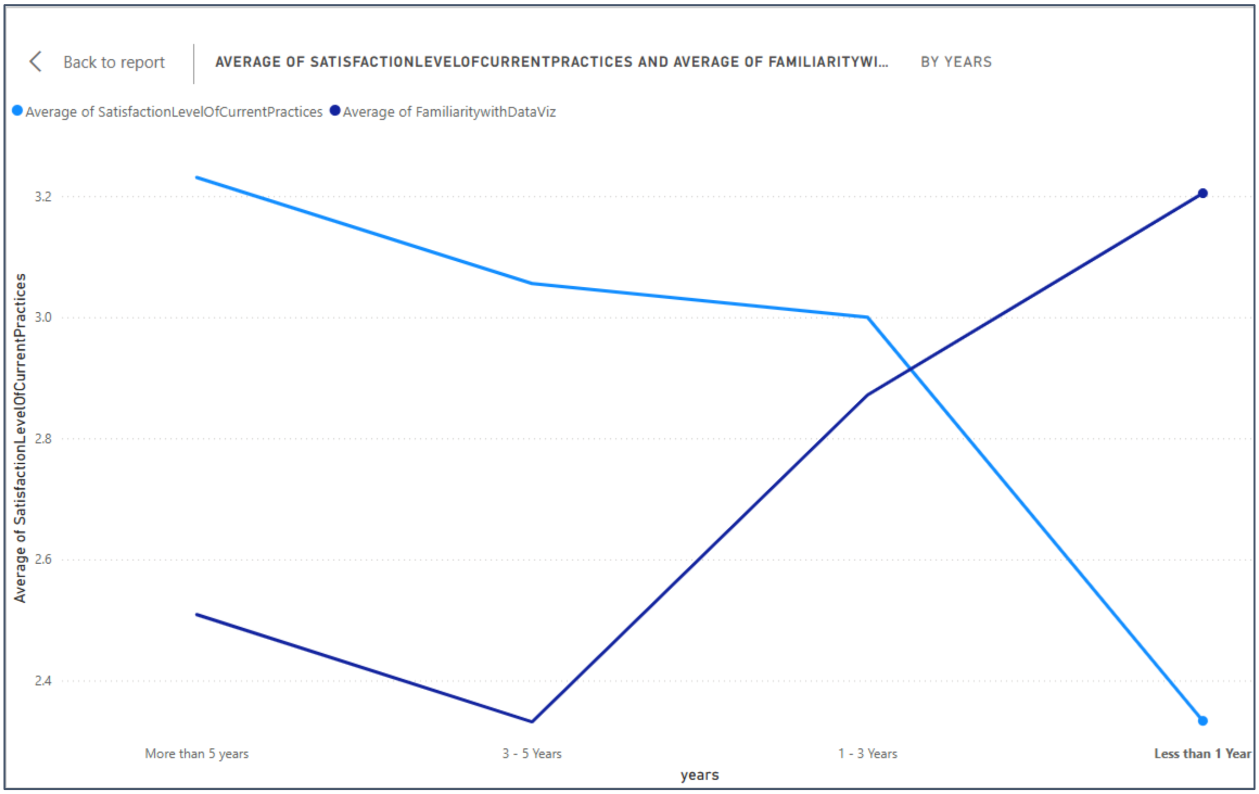
Data Visualization tools decreases with the number of years of professional experience. This implies that newcomers to the profession have been more trained in modern visualization procedures and tools.

Figure 8

Professional Experience and Satisfaction Levels



A Kruskal–Wallis test showed significant differences in satisfaction across experience groups ($\chi^2 = 8.42$, df = 3, p = 0.038), with the highest satisfaction among those with over five years of experience (Mean Rank = 28.4) and the lowest among those with less than one year (Mean Rank = 12.6). In addition, a Chi-square test of independence showed that familiarity was significantly related to satisfaction ($\chi^2 = 10.56$, df = 8, p = 0.022). Nonetheless, the trend pattern showed that respondents more familiar with visualization tools(level 3) were more inclined to express lower satisfaction with the current practices and less familiar respondents (level 1) were more inclined to express relatively high levels of satisfaction. This implies that more informed professionals regarding the latest visualization tools might also be more appreciative of what is actually being done, viewing it as being out of date or not taking advantage of the technologies available.

Discussion

This paper set out to overcome the stagnation between the standardized collection of data and the consequent extraction of actionable intelligence in the Water Service Providers (WSPs) in Nairobi. Although the majority of the providers continuously collect operational data, the results indicate that a lack of sufficient equipment and systems is observed, which could turn the raw data into intelligence that could be utilized in strategic planning and management of operations. In this discussion, the findings are placed with the overall rationale of the study and how a user-informed intervention, i.e., a model of developing data visualization that is specific to the sector, can fill this gap and help in more data-driven, responsive decision-making in the industry.

First, the predominance of an approach using mixed-method monitoring (68.2 %) and ongoing dependency on purely manual practices (11.4 %) shows that WSPs are in an intermediate stage. While digital systems exist, there is still a safeguard through manual inspections. This coexistence highlights the need for a visualization system able to merge automated sensor input and manual data seamlessly. This intermediate dependency on both digital and manual systems is reflected in work by Hope and Ballon (2019), who found that the majority of African utilities implement digital tools through staged integration, relying on manual practices as an intermediary during the initial stages of digital implementation. By merging both data streams onto one dashboard, WSPs can provide an integrated overall view of the operation, minimizing the likelihood that differences between the systems are not caught. In the same vein, Amankwaa et al. (2021) report that in Ghana, digitalization has improved operations but for infrastructural and capacity reasons, manual procedures are still an essential component. This integration thereof has the direct consequence of enabling the basis for breaking beyond passive reporting to active system management.

Secondly, the high focus on throughput and financial metrics, billing effectiveness and total amount dispensed, cuts in stark contrast to the low priority on loss-related metrics such as Non-Revenue Water (NRW). Less than 5% of participants track NRW on a regular basis despite its vital function in system sustainability. From an optimization-resource perspective, the discovery is an important blind spot: unless there is insight into losses, financial metrics cannot indicate shortcomings depleting both revenue and supply. It was noted by Nono et al. (2024) that in Cameroon, NRW rates were at around 52.5% of the system input volume per annum, reflecting high operation ineffectiveness and the need for improved monitoring and management techniques (Victor et al., 2024). An effective visualization model must therefore place NRW and leak-detection rates on the same level as financial KPIs so the decision-maker is able to balance revenue aspirations with infrastructure health. This greater transparency is consistent with the SDG 6 requirement to increase the efficiency of using water and decrease losses.

Thirdly, the strong desire for frequent data updating (52.3 %) substantiates an appetite for near-real-time data. This desire for regular data updating is in agreement with Wainaina et al. (2023), who found that Nairobi City Water and Sewerage Company created an online data gathering tool that enhanced real-time data access and operational response. Poor data cadence has long impacted timely action, whether to quarantine a burst main or realign pump times to rapidly changing demand. By enabling frequent data refresh through the proposed dashboard, rapid anomaly detection and corrective action can be sustained. Real-time capability not only enhances operational resilience but is also the basis for the rationale of the study on converting data into an agility-enabling resource

Furthermore, the operational difficulties cited monitoring and reporting shortcomings, resource allocation problems, and leak detection latency align directly with the top-priority visualization features. The very high demand for straightforward dashboard organization (29 options) and user-configurable views (16 options) stems from practitioners' aspiration to surmount these difficulties through easy-to-use, role-specific interfaces. Mobile accessibility (13 options) accounts for the reality of the field-based workforce who need to access insights on the move, and color-coded indicators (12 options) provide fast triaging of high-priority events. As a whole, these features constitute an integrated solution to the rationale of the study: they allow WSPs to translate uncorrelated data points into an understandable, meaningful picture that aligns operational priorities with strategic goals.

As it can be seen through the analysis of role-specific visualization preferences, various groups of professionals emphasize a variety of features, which highlights the significance of flexible dashboards. ICT officers, NRW specialists, and engineers with the

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biggest expectations on the relevance of historical data comparison, which is more akin to tracking performance and identifying abnormal performance trends. Emphasizing the increased role of spatial intelligence in leak detection, system monitoring, and resource allocation, engineers and HR officers have placed an accent on GIS integration. Monitoring in real-time was highly valued by the operations and maintenance staff, which proves the necessity of tools assisting in monitoring daily operations. All these results help validate the point that although some functionalities, like trend analysis and GIS integration, are widely applicable, the strongest visualization model is more of a role-sensitive and role-specific model applied to a wide variety of professional requirements than being universally uniform.

Further insight is given by the relationship between professional experience, satisfaction and acquaintance with visualization tools. Older professionals who had worked more than five years had greater satisfaction, presumably because they were accustomed to current practices, whereas early-career professionals, trained in modern visualization technologies, showed a greater degree of dissatisfaction, viewing current practices as old-fashioned. A paradox arose concerning the higher the familiarity with the visualization tools, the lower the level of satisfaction was, and that the more informed a user of such tools, the more critical they become about the legacy systems. These observations conform to the diffusion theory of innovation and indicate the necessity of an up-to-date visualization method with predictive analytics, interactive GIS mapping, and role-based design. These models would not only enhance efficiency in the technical aspect but also in matching the expectations of the experienced staff and the new staff to one another.

The combined results of the above investigations reveal that water distribution stakeholders share but have role-specific visualization needs, with variations in degrees of satisfaction depending on professional experience and familiarity with the tools. These pieces of knowledge directly guided the emergence of the conceptual map that was presented in this research. The model should be structured as a role-sensitive, flexible dashboard, which combines the fundamental aspects of the model: historical trend analysis, GIS mapping, and real-time monitoring, but also permits predictive analytics or alert systems. Coordinating the model design with user needs and organizational interests helps eliminate the shortcomings of the current visualization practices identified and offers a way to manage water distribution more efficiently with a data foundation in mind. Based on the findings and the discussion, the resulting proposed model for water distribution management is presented in Figure 9 below.

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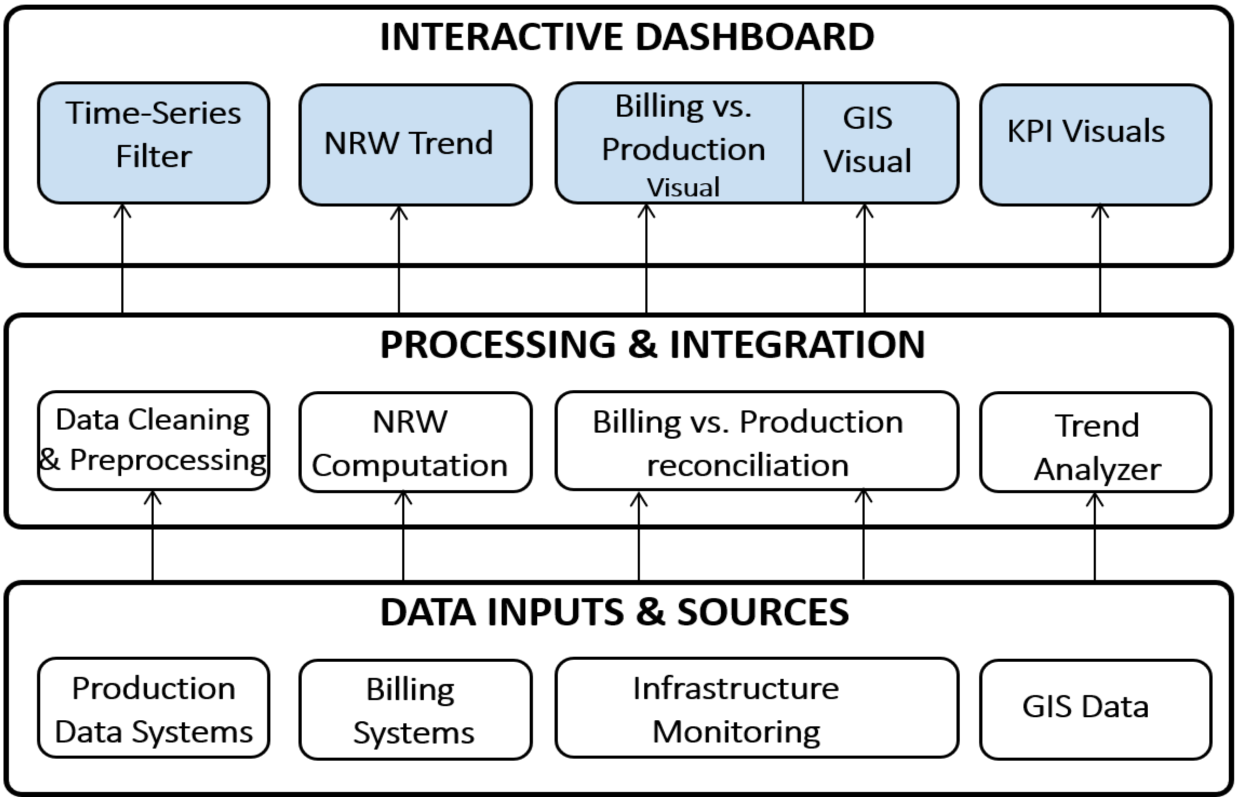
Figure 9

The Proposed Conceptual Model



These results are echoed in global experiences. The California WEAP system proved how interactive, integrated dashboards can lead to stakeholder consensus and strategic planning. Similarly, SABESP's real-time system in Brazil confirmed the gains realized through consolidated monitoring and customer feedback loops.(SEI, 2016) By implementing similar principles, local to the technical capacity and infrastructure limitations of Nairobi's WSPs, this proposed model in the present study has the potential to provide similar gains in terms of both service quality and efficiency.

Besides dashboarding capability, institutional capacity is the key to a satisfactory performance of visualization model in the matter of water distribution. Most WSPs are located in legacy systems that may hamper digital transformation because of the presence of fragmented workflows, minimal IT infrastructure, and insufficient clarity to data governance. Even the most advanced tools can fail to perform well in the scenarios where they are applied to the real-time data that the environment is not ready to process and act upon. It needs a strategic change not only to embrace tools but also the integration of the digital systems with the decision-making process of the organization. Otherwise, visualization initiatives can be watered down into singular technological interventions as opposed to fully integrated components of the operational strategy.

The visualization-based decision-making has to be in line with broader policy and regulation aspects to make it sustainable in the long run. The position of data in governance and accountability can be enhanced by incorporating products of visualization into periodic compliance reports, performance reviews, or in strategic reviews, etc. By placing dashboards as both internal solutions and the means of regulative convergence, WSPs will prove to be transparent, enhance their compliance with rules and regulations, and establish an inertia of innovation in the execution of public services. Additionally, the policy convergence stands a better opportunity to scale up model acceptance to more than one region, and thus, scalability and standardization of the solution used by several utilities with similar problems afflicted to them.

Conclusion and Recommendations

The paper emphasizes a much-needed paradigm shift in the management of water distribution by WSPs in Nairobi Metropolitan Area. Many providers do not have full digital integration, but offer systems that are more based on hybrid, requiring control through automation, as well as manual control, a fact that supports the need of the visualization models that will be able to integrate both. The existing practices are excessively based on financial metrics at the expense of essential metrics associated with losses like NRW and leak detection, thus compromising the long-term sustainability. Moreover, the fact that a vast number of people require quick updates of data and real-time information reflects the significance of responsive systems which will assist in predictive maintenance and identification of anomalies. Not less significant is the plea of plain, personalized, and role aware interfaces to support the idea of integrating the principles of user-centered designs in future visualization tools.

It is on the basis of these insights that this study presents a recommendation to Water Service Providers (WSPs) in the Nairobi Metropolitan Area to enhance their operational efficiency through the integration of data in a hybrid manner. Visualization systems will need to be built or purchased to support a combination of manual and automated data feeds so they can provide a complete view of day-to-day operations. It is also suggested that WSPs should re-weight performance parameters to be more reliant on loss-related data, including Non-Revenue Water (NRW), leakage detection rate, and downtimes, and money books, including billing efficiency. Having such measures at the forefront will facilitate long-term sustainability and resource optimization instead of viewing the whole situation within short-term financial performance.

Also, WSPs must implement predictive and real-time monitoring into their visualization models. Options like automatic warning features, anomaly detection, and a fast update on the data would be highly recommended since that would facilitate timely intervention during preventive maintenance. Moreover, the design of dashboards must align with user-centered principles--they should be personalized, mobile, and user-friendly across categories of users such as field technicians and top managers. That would enhance usability and make the system approach the practical needs of all stakeholders.

Lastly, both utilities and regulators should invest in policy alignment and institutional capacity is a recommendation. Employees must be empowered through the skills of analyzing data as it appears and how to react to such trends to turn the dashboard into an active decision-support mechanism instead of a dormant reporting tool. Policy and regulators must also advance data-driven practice at the policy level to implement practices that underlie Sustainable Development Goals (SDG 6 and SDG 11), as quality performance metrics must include visualization instruments. These two investments in human potential and policy predictability will play a critical role in attaining sustainable and efficient distribution management of water.

Declaration of generative AI and AI-assisted technologies in the writing process

In writing this manuscript, the author(s) used Zotero to organize references and produce in-text citations and bibliographic lists. Grammarly was also for spell checking and grammar refinement. After implementing these tools, the authors conducted a thorough review and revision process to provide accuracy, clarity, and scholarly integrity. The authors of the manuscript accept full responsibility in regard to the final content of the manuscript.

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CRediT authorship contribution statement

Abel Mulongo: Conceptualization, Data Collection, Data Curation, Formal Analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Dr. James Abila: Conceptualization, Methodology, Supervision, Writing – Original Draft, Writing – Review & Editing, Validation. Dr. Lamek Ronoh: Conceptualization, Methodology, Supervision, Writing – Review & Editing, Validation.

All authors contributed to the review of the final manuscript and approved it for publication.

Declaration of conflict of interest

The authors declare that there are no financial, personal, or professional conflicts of interest that could be perceived to influence the findings or interpretations presented in this work.

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References

AbuEltayef, H. T., AbuAlhin, K. S., & Alastal, K. M. (2023). Addressing non-revenue water as a global problem and its interlinkages with sustainable development goals. *Water Practice and Technology*, *18*(12), 3175–3202. https://doi.org/10.2166/wpt.2023.157

Andrienko, G., Andrienko, N., Drucker, S., Fekete, J.-D., Fisher, D., Idreos, S., Kraska, T., Li, G., Ma, K.-L., Mackinlay, J., Oulasvirta, A., Schreck, T., Schumann, H., Stonebraker, M., Auber, D., Bikakis, N., Chrysanthis, P., Sharaf, M., & Papastefanatos, G. (2020, February 1). *Big Data Visualization and Analytics: Future Research Challenges and Emerging Applications*.

Chunyang, H., Jianguo, W., Xinhao, Zihang, F., Jingwei, L., & Brett A., B. (2021, August 3). *Future global urban water scarcity and potential solutions | Nature Communications*. https://www.nature.com/articles/s41467-021-25026-3

Fry, B. (2008). *Visualizing Data*.

Grigg, N. S. (2024). Water Distribution Systems: Integrated Approaches for Effective Utility Management. *Water*, *16*(4), Article 4. https://doi.org/10.3390/w16040524

Gupta, S. P., & Pandey, U. K. (2019). *Data Analysis, Visualization, and Leak Size Modeling for Water Distribution Network*. *898*, 77–83. https://doi.org/10.1007/978-981-13-3393-4_9

Küfeoğlu, S. (2022). SDG-11: Sustainable Cities and Communities. In S. Küfeoğlu (Ed.), *Emerging Technologies: Value Creation for Sustainable Development* (pp. 385–408). Springer International Publishing. https://doi.org/10.1007/978-3-031-07127-0_13

Mona Batra & Archana Bhatnagar. (2019). *(PDF) Requirements Elicitation Technique Selection: A Five Factors Approach*. *8*(5c), 1332–1341. https://doi.org/10.35940/ijeat.E1190.0585C19

namsip. (2023). *The-Nairobi-Metropolitan-Region.jpg (970×1254)*. https://namsip.go.ke/wp-content/uploads/2018/05/The-Nairobi-Metropolitan-Region.jpg

Ngueyim Nono, K. J., Dang Mvongo, V., & Defo, C. (2024). Assessment of non-revenue water in the urban water distribution system network in Cameroon (Central Africa).

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Water Supply, *24*(5), 1755–1767. https://doi.org/10.2166/ws.2024.071

O'Connor, J., Parman, M., Bowman, N., & Evergreen, S. (2023). Decolonizing Data Visualization: A History and Future of Indigenous Data Visualization. *Journal of MultiDisciplinary Evaluation*, *19*. https://doi.org/10.56645/jmde.v19i44.783

Oladipupo et.al, B. (2019, February 14). *Water | Free Full-Text | Solving Management Problems in Water Distribution Networks: A Survey of Approaches and Mathematical Models*. https://www.mdpi.com/2073-4441/11/3/562

Qin, X., Luo, Y., Tang, N., & Li, G. (2020). Making data visualization more efficient and effective: A survey. *The VLDB Journal*, *29*(1), 93–117. https://doi.org/10.1007/s00778-019-00588-3

Ranjitha Bai A, Kavyashree H S, Ananya, Gnaneshwar, & Tilak. (2024). DATA SCIENCE: Data Visualization and Data Analytics in the Process of Data Mining. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT*, *08*, 1–10. https://doi.org/10.55041/IJSREM28332

Schunke, L., Luna de Oliveira, L. P., & Villamil, M. (2014). Visualization and analysis of interacting occurences in a smart city. *Proceedings - International Symposium on Computers and Communications*. https://doi.org/10.1109/ISCC.2014.6912490

SEI, U. (2016, November 28). *How data visualizations can help build a 'mental map' of complex water resource problems*. SEI. https://www.sei.org/perspectives/visualizing-water-problems/

WASREB. (2023). *Impact Report Issue No. 15 – Welcome to Wasreb*. https://wasreb.go.ke/impact-report-issue-no-15/