Transformation of Urban Sewer Network Management through GIS: Enhancing Operational Efficiency, Revenue Generation, and Environmental Sustainability

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Abstract

Effective management and expansion of sewer networks are vital for sustainable urban development and environmental protection. Traditional approaches, often reliant on manual surveys and assessments, suffer from inefficiencies, high labor costs, and delayed decision-making. This study introduces an advanced Geospatial Information Systems (GIS) framework that not only revolutionizes operational workflows but also contributes to increased revenue through expedited connection allocations and reduced maintenance costs. In the cities of Isfahan and Khomeinishahr, the proposed methodology integrates multiple data layers—including detailed sewer infrastructure (treatment plants, manholes, collection pipelines, and pumping stations), comprehensive subscriber databases, and cadastral records—to perform high-resolution spatial analyses. The process involves systematic steps such as descriptive data extraction, GIS data synchronization, precise distance calculations from existing sewer lines, and classification of subscribers into prioritized groups (e.g., within 8 meters for immediate connection, 8–20 meters for network extension, and beyond 20 meters for network redesign). Field validation confirms an accuracy rate of approximately 95%, while the overall planning time is reduced. Additionally, by automating the identification of unconnected subscribers, this GIS-based solution accelerates revenue generation through faster connection sales and more efficient resource allocation. Beyond immediate operational benefits, transitioning from localized septic systems to centralized sewer networks significantly mitigates environmental risks—reducing soil and groundwater contamination and promoting long-term sustainability. Overall, the results demonstrate that the enriched GIS approach not only enhances the precision of urban sewer management but also lays a scalable framework for future smart infrastructure initiatives, combining enhanced operational efficiency with tangible economic and environmental benefits.

1. Introduction

The management and expansion of sewer infrastructure are critical for achieving sustainable urban development and ensuring environmental protection. Traditional methods—predominantly relying on manual surveys and assessments—are not only labor-intensive and time-consuming but also fail to capture the comprehensive needs of modern urban communities. In response, this study leverages Geographic Information Systems (GIS) to enhance the management of sewer networks in Isfahan and Khomeinishahr through targeted spatial analysis, thereby improving operational efficiency, strategic planning, and resource allocation in resource-constrained urban environments.
Recent technological advances and the proliferation of high-resolution spatial data have fundamentally transformed GIS-based spatial analysis. Early approaches, such as weighted overlay techniques, enabled practitioners to integrate diverse data layers (e.g., land use, vegetation cover, slope) by assigning appropriate weights to each, thus facilitating the extraction of spatial patterns critical for infrastructure planning. Building on these foundations, multi-criteria decision-making methods—such as the Analytic Hierarchy Process (AHP) (T.L. Saaty, 2004, 2008) and its extension, the Analytic Network Process (T.L. Saaty, 2004)—have provided more precise and flexible frameworks for modeling complex interrelationships among urban planning criteria.
In the past decade, the integration of machine learning algorithms (including neural networks, random forests, and Support Vector Machines) into GIS has further enhanced the accuracy and efficiency of spatial analyses (H.R. Pourghasemi et al., 2020; N.N. Thanh et al., 2022). These algorithms exploit large, multi-source datasets to uncover hidden patterns and yield more reliable predictions of environmental and urban variables (M. Goodchild et al., 1992; A. Azizi et al., 2017; M. Duckham et al., 2023). The fusion of weighted overlay methods, ANP, and machine learning represents a significant methodological advance, offering comprehensive evaluations of spatial data and delivering practical insights for urban planning, crisis management, resource allocation, and environmental risk assessment (A. Azizi et al., 2025).
In the present study, we evaluate the practical applications of Geospatial Information Systems (GIS) in the management of urban sewage infrastructure, building on established GIS techniques while adapting them to local challenges in Iranian cities. This research aims to enhance the operational efficiency and sustainability of sewage networks in targeted cities, as well as to improve customer satisfaction through the provision of superior services and cost-effective resource use. The analytical methods employed in this study incorporate the use of GIS spatial layers alongside spatial and descriptive data mining analyses, enabling comprehensive identification and optimization of existing potentials within urban sewage networks. While advanced machine learning integrations are noted in recent literature, this work focuses on foundational GIS

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implementations to provide immediate, actionable outcomes, with potential for future ML enhancements.

The application of GIS in this research allows us to present context-specific perspectives on the management and operation of sewage networks and to contribute to standards for the development of vital infrastructure. Unlike previous theoretical studies that primarily focused on preliminary locational analyses, this study adopts a more practical approach (L.K. Singh et al., 2018; R. Das and S. Saha, 2022), emphasizing tangible operational outcomes such as reduced maintenance costs and accelerated revenue generation. The results not only improve the compatibility and efficiency of existing systems but also pave the way for future transformations in urban infrastructure management, including economic evaluations of long-term benefits. Thus, the applied potential of GIS in urban management can serve as a benchmark for the continual assessment and enhancement of sewage infrastructure systems.

Moreover, transitioning from decentralized septic systems to centralized sewer networks offers considerable environmental, infrastructural, and economic advantages. The integration of households into a centralized system promotes infrastructure sustainability by ensuring uniform utilization of sewer pipelines, which not only minimizes maintenance requirements but also extends the overall operational lifespan of the network while reducing long-term costs associated with environmental remediation.

This paper specifically examines the deployment of GIS for sewer management in Isfahan and Khomeinishahr with the following objectives:

- **Identification of Unconnected Subscribers:** To pinpoint households eligible for sewer connection allocation, thereby extending essential services to underserved communities and generating revenue through efficient connections.
- **Environmental Impact Mitigation:** To reduce environmental hazards by transitioning from septic systems to centralized sewer networks, enhancing public health and ecological integrity while lowering pollution-related costs.
- **Optimization of Sewer Network Usage:** To prevent infrastructure deterioration due to underutilization, ensuring the long-term reliability and efficiency of the sewer system.
- **Strategic Infrastructure Planning:** To identify areas requiring network development and support proactive planning for future expansions and upgrades, incorporating economic assessments for cost-benefit optimization.

2. Study Area Description

The cities of Isfahan and Khomeinishahr, located in central Iran, are integral to the study of urban sewer management due to their unique infrastructural and cultural characteristics. Isfahan, situated at approximately 32.6546° N, 51.6675° E, is not only a major urban center but also a cultural and historical hub, renowned for its architectural beauty and historical significance. This city's extensive sewer network, spanning approximately 4,500 kilometers, caters to the needs of a densely populated and culturally rich area. Efficient management of such a vast network requires an integrated spatial data repository capable of handling and analyzing complex data to support extensive reach and diverse usage patterns.

The use of Geospatial Information Systems (GIS) in these settings is crucial for precise mapping, monitoring, and analysis of the sewer networks, which facilitates effective maintenance, timely upgrades, and strategic planning. This integrated approach is essential for maintaining infrastructure resilience and ensuring the environmental sustainability of water management practices in these culturally and historically significant cities.

Additionally, it is crucial to investigate and address the needs of subscribers without sewer connections. Focusing on these unconnected subscribers facilitates targeted improvements in sanitation, environmental health, and overall quality of life. This effort not only extends essential services to underserved populations but also supports strategic sewer network expansion, ensuring equitable access and resource distribution. Identifying and integrating these subscribers is vital for the comprehensive management and sustainable development of urban infrastructure.

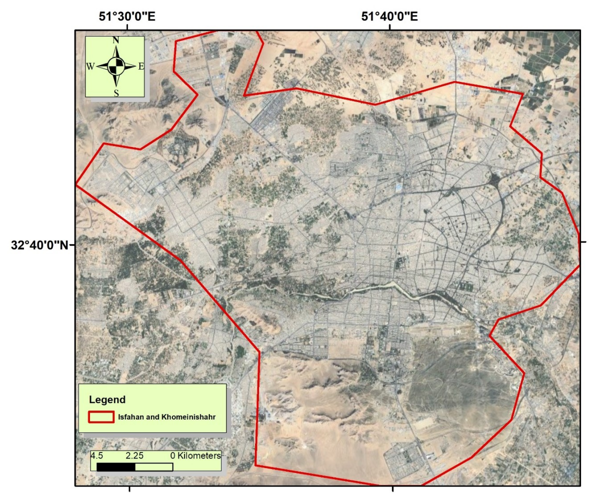

Figure 1. Geographical extent of the study area

3. Spatial database and Methodology

As demonstrated in Figure 2, this section describes the integration of Geographic Information Systems (GIS) with sewer network management, deploying a rigorous and systematic method for spatial data handling and infrastructure development. The spatial database and methodology detailed herein are pivotal for managing and analyzing the complexities of the sewer system.

This flowchart delineates the steps and strategies for integrating GIS with sewer network management, facilitating analysis and decision-making processes in accordance with high-quality journal standards.

3.1 Spatial database

The study utilizes several key components within the GIS framework to manage and analyze the sewer network efficiently:

Sewer Network Infrastructure: This includes:

- **Treatment Plants:** Facilities where sewage is treated to meet legal standards before being released into the environment.

- **Manholes:** Access points for maintenance and monitoring of the sewer system.
- **Sewer Collection Pipes:** Channels through which wastewater is conveyed from various locations to treatment plants.
- **Pumping Stations:** Facilities that help in moving wastewater from lower to higher elevation areas, especially in regions where direct gravity flow is not feasible.
- **Subscriber Layer:** This layer in GIS contains precise locations of all subscribers, integrated with detailed attributes such as the status of sewage and water connections, along with other data such as land use and consumption levels. This comprehensive dataset is crucial for analyzing service coverage and planning infrastructure development.
- **Parcel Layer:** Includes detailed cadastral data which helps in understanding property boundaries. This layer is used to assess the potential impact of sewer network expansions on private and public land, facilitating negotiations and compliance with local land use regulations.

3.2 Integrating GIS with Sewer Network Management: A Detailed Workflow Analysis

Figure 2 presents a sophisticated and systematic workflow for integrating Geospatial Information Systems (GIS) with sewer network management, employing a comprehensive approach for spatial data analysis and infrastructure planning. The stages of the process are as follows:

1) **Initiation with Descriptive Inquiry:** The workflow begins with a detailed descriptive inquiry leveraging subscriber data and GIS layers. This initial phase focuses on extracting crucial information regarding sewer connectivity status from the subscriber database, including geographical coordinates, service status, and connectivity details, which are essential for integration with physical GIS layers.

   Integration of Manhole and Collection Network Data: In this stage, data related to sewer manholes and the collection network are integrated into the GIS. This process involves mapping all relevant physical infrastructure elements, such as manholes, pipelines, and sewer lines, to provide a spatial understanding of the existing assets and their conditions. The integration facilitates the identification of gaps in sewer coverage and potential areas for future network expansion.

2) **GIS Data Entry and Synchronization:** This phase involves entering and synchronizing sewer network data with subscriber information within the GIS platform. The integration of these datasets enables spatial queries and analyses that are pivotal for subsequent calculations of distance and infrastructure planning.

3) **Distance Calculation from Sewer Network:** At this stage, the precise distance from each subscriber's location to the nearest sewer pipeline is calculated. This information is essential for assessing the feasibility of connecting subscribers to the existing infrastructure and planning for the extension of the network where necessary.

4) **Categorization Based on Proximity to Sewer Network:** Subscribers are categorized according to their proximity to the sewer network, based on the calculated distances. Three categories are defined:

   - Subscribers within 8 meters of the sewer network are considered ready for immediate connection.
   - Subscribers situated between 8 and 20 meters require network extension.
   - Subscribers located beyond 20 meters necessitate a new network design to enable connectivity.

5) **Categorization Based on Key Features:** As part of the analysis, subscriber categorization is further refined based on expert assessments and field evaluations, yielding the following critical features:

   - **Land Use:** Subscribers using commercial properties with parcels smaller than 50 square meters typically do not require access to sewer network infrastructure. This helps optimize resource allocation by focusing infrastructure development efforts on areas with greater demand.
   - **Consumption Levels:** Subscribers with average daily water consumption below 50 liters per second generally do not require sewer network connections. This criterion allows for the efficient targeting of high-demand users, ensuring that resources are directed where they are most needed.

   These key parameters facilitate a more structured and effective approach to improving sewer network efficiency and support the strategic planning of infrastructure upgrades and expansion in urban areas.

6) **Field Verification:** Field verification involves on-site assessments to validate GIS data categorizations. Teams verify the physical, environmental, and logistical factors that could impact the feasibility of proposed extensions or new infrastructure, ensuring the accuracy of the planned developments.

   Operational Report and Strategic Mapping: An extensive operational report is generated, complemented by detailed GIS maps illustrating categorized subscriber locations and proposed infrastructure modifications. These documents serve as essential tools for engineers and planners, providing a strategic framework for phased implementation.

7) **Conclusion of Process:** The process concludes with the review and approval of operational plans and

strategic maps. This step ensures the smooth transition from analysis to practical implementation, supported by comprehensive data and strategic insights.

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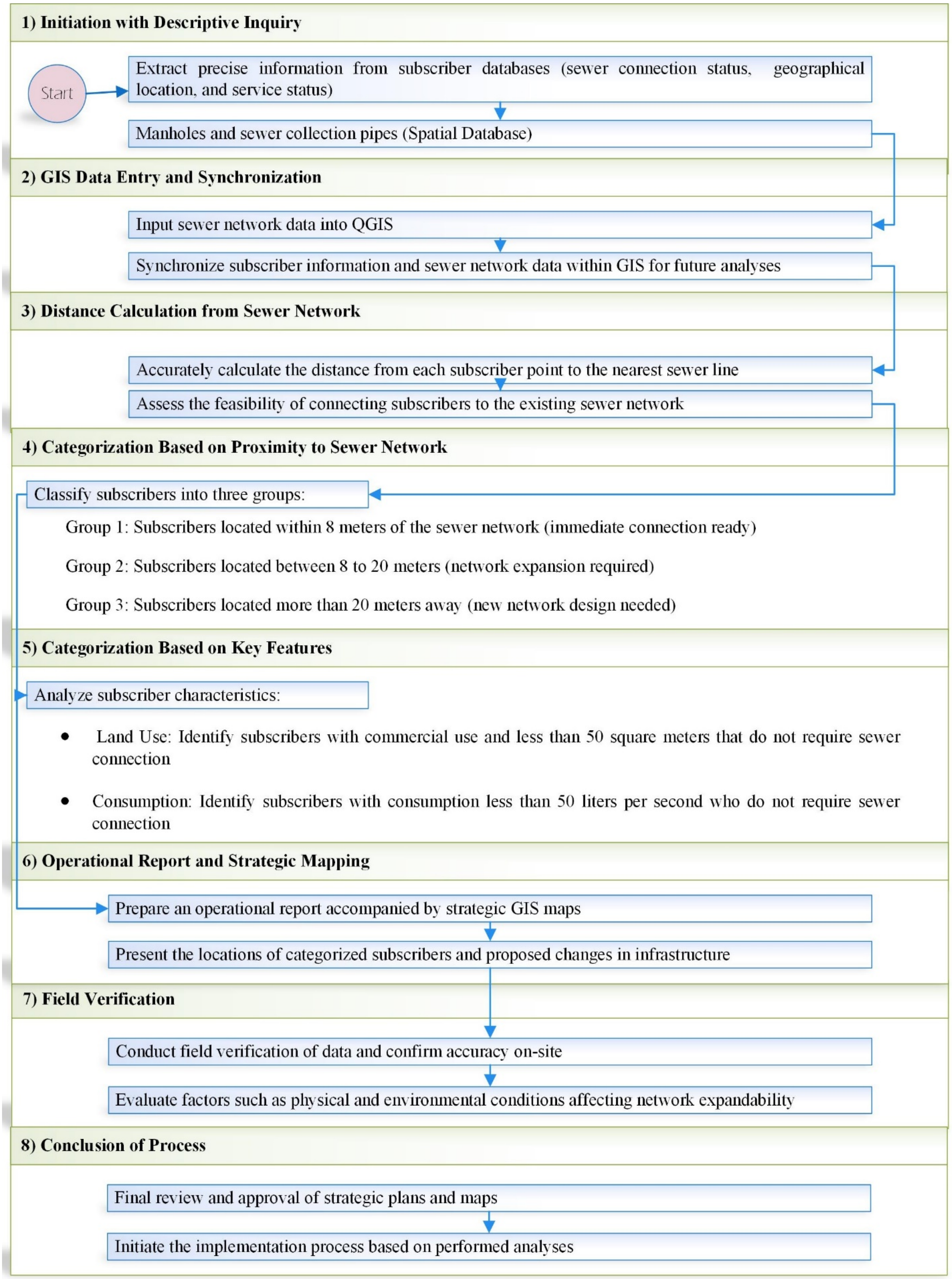

Figure 2. Flowchart for Integrating GIS with Sewer Network Management

4. Results

This study presents the integration of Geospatial Information Systems (GIS) with sewer network management to improve planning efficiency and infrastructure optimization in the regions of Isfahan and Khomeineishahr City. By combining updated subscriber datasets with high-resolution GIS-based physical layers, the spatial accuracy and completeness of the sewer network were significantly enhanced. Precise location of infrastructure elements such as manholes and pipelines allowed for the identification of existing service gaps and high-potential expansion zones, thereby supporting more informed and targeted planning decisions.

4.1 Subscriber Distribution and Connection Potential

A targeted analysis was conducted on subscribers who were connected to the municipal water supply network but had no access to the sewer infrastructure. Spatial proximity analysis revealed that:

- 19.4% of subscribers are located within 8 meters of the existing sewer infrastructure,
- 29.1% are located between 8 and 20 meters,
- and 51.5% are situated more than 20 meters away.

Among subscribers connected to the water network but not yet to the sewer system, approximately 19.4% fall within 8 meters of the existing sewer lines—indicating a high potential for low-cost, high-impact network extensions.

This stratification enabled a focused reduction in the target population from the entire subscriber base to a 19.4% subset with the highest spatial suitability for sewer connection. This refinement improves operational efficiency and prioritizes infrastructure investment.

4.2 Refined Targeting Based on Land Use and Water Consumption

To further prioritize among the 19.4% subset, two critical parameters were introduced:

Land Use: Properties primarily designated for commercial use and with parcel sizes smaller than 50 m² were excluded, as such units typically do not necessitate sewer connections.

Water Consumption: Subscribers with average daily water usage below 50 liters per second were also excluded due to their minimal wastewater generation.

After applying these filters, approximately 3.9% of the total subscribers met both conditions and were identified as priority candidates for sewer connection in the next phase of infrastructure expansion.

4.3 GIS-Based Mapping and Spatial Prioritization

GIS-based spatial analysis enabled precise calculation of distances between existing sewer pipelines and subscriber locations. This data-driven approach allowed for the prioritization of previously unconnected subscribers located within an 8-meter radius for immediate service enhancement. As a result, resource allocation was optimized, unnecessary expenditures were reduced, and network expansion in high-potential areas was accelerated.

Figure 3. Visualization of selected unconnected subscribers alongside the existing sewer network and parcel boundaries.

Furthermore, subscribers identified as candidates for the design and implementation of new sewer segments are presented spatially in the following map.

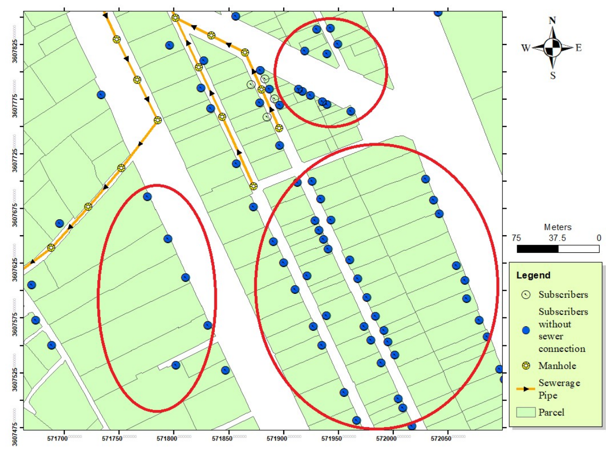

Figure 4. Display of Areas Requiring Design

4.4 Enhanced Decision-Making Efficiency

The integration of GIS tools produced comprehensive operational reports and strategic maps, significantly improving the decision-making process. With access to timely and accurate data, engineers and urban planners reduced planning time, leading to more effective and informed strategic decisions.

4.5 Streamlined Operational Workflow

The availability of detailed maps and precise spatial data via GIS simplified the operational workflow associated with identification, planning, and resource allocation. This streamlining facilitated the more efficient deployment of human and technical resources, thereby improving overall system performance.

4.6 Economic and Service Benefits

Beyond operational improvements, the integration of GIS into sewer network management resulted in increased revenue through optimized service delivery and enhanced subscriber satisfaction. These benefits have contributed to a faster pace of infrastructure development and greater cost-effectiveness. A detailed economic analysis, including a cost-benefit assessment, will further validate the long-term profitability and sustainability of these initiatives. By evaluating both the costs of implementation and the projected long-term savings from optimized infrastructure planning, this study lays the groundwork for a comprehensive economic model that supports future expansion.

5. Discussion

The integration of Geospatial Information Systems (GIS) with sewer network management in Isfahan and Khomeneishahr City has led to substantial advancements in operational efficiency, infrastructure planning, and environmental sustainability. By combining updated subscriber data with high-resolution GIS spatial layers, this approach significantly enhanced the spatial accuracy and resolution of the sewer network information, ultimately facilitating more efficient infrastructure development. This methodological integration has allowed for targeted interventions and optimized resource allocation, directly contributing to improved service delivery.

One of the notable outcomes of this study was the effective automation of subscriber classification based on their spatial relationship to existing sewer infrastructure. This automation not only streamlined operational workflows but also significantly reduced the need for time-consuming field inspections. Spatial proximity analysis of the subscribers no access to the sewer infrastructure revealed that approximately 19.4% were located within 8 meters of existing sewer lines, 29.1% between 8 and 20 meters, and 51.5% beyond 20 meters. By narrowing the focus to the 19.4% located within the most favorable proximity, the study identified a priority subset with the highest potential for cost-effective and technically feasible sewer connections. This refinement allowed for more efficient resource allocation and reduced implementation complexity, particularly in urban areas with limited infrastructure access.

To ensure further precision in planning, the analysis incorporated two additional subscriber attributes: land use type and average daily water consumption. Properties primarily designated for commercial purposes and measuring less than 50 square meters were excluded, as they typically do not generate sufficient wastewater volumes to justify connection. Similarly, subscribers with average water consumption below 50 liters per second were also excluded, given their limited contribution to the overall sewer load. As a result of applying these filters, the candidate pool was reduced to approximately 3.9% of the total subscribers—representing the most suitable and impactful targets for immediate infrastructure expansion.

This multi-criteria refinement approach not only prioritized technical feasibility but also ensured that investments were directed toward areas with demonstrable service demand. In doing so, it optimized both operational efficiency and financial performance. Moreover, by reducing the dependency on manual site surveys and improving the accuracy of spatial targeting, the methodology established in this study provides a replicable model for other cities facing similar infrastructure challenges.

The integration of GIS also significantly improved the accuracy and reliability of service mapping, allowing for the precise identification of unconnected subscribers and gaps in network coverage. Detailed mapping of infrastructure components such as manholes and pipelines provided real-time, spatially accurate data for decision-makers. This enhanced precision facilitated the prioritization of high-need areas and streamlined the allocation of resources for network expansion. GIS technology ensured that interventions were targeted more effectively, reducing inefficiencies and ensuring timely infrastructure development.

In terms of project scheduling, GIS-based spatial analysis contributed to a significant reduction in planning time. By enabling the rapid identification of serviceable areas and connection-eligible subscribers, the overall project timeline was reduced. For example, in a case where manual surveys and assessments typically took several months, GIS tools facilitated a more efficient identification process, accelerating sewer connection sales and infrastructure development. This improvement in project timelines not only optimized resource deployment but also enhanced customer satisfaction and the responsiveness of urban planning.

Beyond operational improvements, the integration of GIS provides a robust foundation for long-term infrastructure development. The spatial intelligence derived from GIS enables municipal planners to forecast future demand patterns, optimize network expansion strategies, and ensure that resources are allocated sustainably. This system-driven approach facilitates the proactive management of infrastructure lifecycles, helping to extend the longevity of networks and mitigate the impact of capacity constraints. Additionally, GIS technologies support continuous refinement in decision-making processes, allowing for adaptable and data-driven urban planning strategies.

Another significant benefit of transitioning from decentralized septic systems to centralized sewer networks is the reduction in environmental degradation. Septic systems, especially in densely populated urban areas, often lead to groundwater contamination due to poorly managed wastewater discharge. The shift to a centralized sewer network helps to minimize pollutant infiltration, reducing the risk of waterborne diseases and enhancing public health. Moreover, centralized wastewater treatment processes contribute to ecosystem preservation by maintaining water quality and promoting ecological resilience. This environmental benefit is crucial for meeting sustainability goals while improving urban living conditions.

Effective sewer network utilization is critical to preventing infrastructure degradation. Underutilized networks can suffer from long-term deterioration due to sedimentation and inefficient flow, while overburdened systems experience wear and frequent service disruptions. GIS-driven spatial analysis enables municipalities to identify zones of suboptimal usage, assess vulnerabilities, and implement corrective interventions. This proactive approach helps to maintain infrastructure integrity, reduce operational costs, and ensure service reliability in the long run.

While the study identified 3.9% Subscribers without sewer connection as potential candidates for sewer connections, not all of them may be immediately eligible due to consumption patterns and infrastructure constraints. A phased

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implementation strategy is recommended, with priority given to subscribers who exhibit higher feasibility for connection. Further data analysis should refine eligibility criteria. Incorporating additional parameters such as property type, population density, and the condition of existing networks will improve the decision-making framework. By integrating these variables into a dynamic, data-driven strategy, planners can better allocate resources to areas with the highest impact potential, optimizing both service delivery and public health outcomes.

6. Conclusion

The integration of Geospatial Information Systems (GIS) into sewer network management has proven to be a transformative advancement in urban infrastructure planning. This study demonstrates that GIS not only enhances the operational efficiency of sewer network management but also plays a crucial role in long-term sustainability and environmental stewardship. By leveraging high-resolution spatial analytics, this approach optimizes resource allocation, accelerates project timelines, and improves service accuracy, resulting in a more efficient and effective wastewater management system.

The findings highlight GIS's significant impact in addressing operational challenges and environmental concerns. Through precise spatial mapping, the identification of infrastructure gaps, and the optimization of network utilization, GIS provides a scalable framework adaptable to various urban contexts. Moreover, by reducing environmental degradation and ensuring compliance with public health standards, GIS contributes to the overall sustainability of urban wastewater management systems.

As urban areas continue to expand, the role of GIS in predictive infrastructure planning becomes increasingly vital. Future research should focus on refining GIS models and incorporating real-time monitoring to further enhance the resilience and adaptability of sewer networks. Expanding the use of spatial analytics in predictive modeling will help future needs and reduce potential disruptions.

Additionally, a thorough economic analysis, including long-term profitability projections and cost-benefit assessments, will provide a more comprehensive understanding of the financial implications of GIS integration. Such analysis will further enhance the value of GIS in improving cost-effectiveness and the sustainability of urban infrastructure projects.

In conclusion, the integration of GIS into sewer network management provides a comprehensive, data-driven approach to urban infrastructure development. By improving spatial accuracy, optimizing resource allocation, and enhancing the efficiency of infrastructure expansion, GIS technology lays the foundation for more effective, sustainable, and resilient urban planning. This framework, when applied in broader urban contexts, can significantly improve sewer network management, contributing to healthier urban environments and more efficient resource utilization.

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