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# Geo-Hydraulic Optimization of Gravity Sewer Networks Using GIS and Population Forecasting: Sustainable Design Framework for Semi-Urban Okara Case Study

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## Abstract

Urban drainage systems in developing semi-urban regions face increasing pressure due to rapid population growth, unplanned development, and inadequate sanitation infrastructure, leading to environmental degradation and public health risks. In many such areas, conventional wastewater disposal through open drains remains prevalent, highlighting the urgent need for engineered sewerage solutions that are both sustainable and adaptable to future urban expansion. The purpose of this study is to develop a GIS-integrated, hydraulically optimized sewerage system for Chak 19, Okara, with a novel approach that combines population forecasting, hydraulic modeling, and spatial analysis for improved design accuracy and sustainability. The novelty lies in the integrated application of demographic prediction models, Manning-based hydraulic design, and GIS-based spatial alignment within a single unified framework for semi-urban sewer planning. Methodologically, the study employs a 35-year design horizon and applies arithmetic, incremental, and geometric population forecasting methods to estimate future demand. Wastewater generation is calculated using standard per capita water consumption rates with peak flow adjustments. The sewer network is designed using gravity-based principles and analyzed through Manning's equation to ensure hydraulic efficiency. Geographic Information System (GIS) tools are utilized for spatial mapping, slope determination, and alignment optimization, while field GPS data ensure accurate georeferencing of the network layout. The sewage treatment plant is located based on topographic suitability and hydraulic feasibility. The results indicate that the proposed system effectively accommodates projected population growth while maintaining self-cleansing velocities and hydraulic stability across all sewer segments. GIS integration enhances spatial accuracy and system planning efficiency, while gravity-based design reduces operational costs. Overall, the study presents a robust, scalable, and sustainable framework for urban sanitation infrastructure development in semi-urban regions.

**Keywords:** Urban Drainage Systems; Sewerage Design; GIS Integration; Hydraulic Modeling; Population Forecasting; Stormwater Management; Sustainable Infrastructure

## Highlights

- Integrated GIS, population forecasting, and hydraulic design.
- GIS-based gravity systems improve efficiency, reduce costs.
- Scalable design ensures growth and self-cleansing reliability.



## Introduction

Urban drainage systems have evolved from rudimentary sanitation structures in ancient civilizations to highly engineered and increasingly data-driven infrastructure networks in modern cities [1]. Early systems in Mesopotamian and Indus Valley settlements relied on open channels for basic wastewater disposal and flood protection, while Roman engineering introduced covered sewer networks emphasizing public health and urban hygiene [2]. With industrialization and rapid urban expansion, drainage systems shifted toward centralized sewer networks designed primarily for rapid stormwater and wastewater conveyance [3]. However, this transition significantly altered natural hydrological processes by increasing impervious surfaces, reducing infiltration, and amplifying surface runoff and peak discharge rates [4]. In contemporary urban environments, these challenges have intensified due to climate change, unplanned urban growth, and increased rainfall variability, rendering conventional drainage systems insufficient to manage emerging hydrological extremes.

Despite significant advancements in hydraulic engineering and urban water management, existing drainage systems continue to face critical limitations in terms of adaptability, efficiency, and environmental sustainability [5]. Conventional grey infrastructure, although effective in controlled conveyance of stormwater, often fails under extreme precipitation events and contributes to environmental degradation through pollutant transport and hydrological disruption [6]. While hydraulic modeling tools such as SWMM and MIKE-based platforms have improved system analysis, and optimization algorithms have enhanced design efficiency, these approaches are often applied independently, limiting their combined potential [7]. Similarly, GIS and Remote Sensing technologies are widely used for spatial analysis and flood mapping; however, their integration with hydraulic and optimization frameworks remains fragmented [8]. This lack of integration represents a key research gap in current urban drainage studies, particularly in developing regions where data scarcity further constrains robust system design and evaluation. The primary aim of this study is to develop a comprehensive and integrated framework for urban drainage system analysis by combining hydraulic modeling, optimization techniques, and geospatial technologies to enhance flood resilience, system efficiency, and sustainability. The specific objectives include: (i) to evaluate the performance of urban drainage systems under varying hydrological and climatic conditions using SWMM-based hydraulic simulation, (ii) to optimize sewer network design parameters such as pipe diameter, slope, and layout using advanced heuristic and AI-based optimization techniques, (iii) to incorporate GIS and Remote Sensing datasets for accurate spatial representation of urban catchments and runoff characteristics, and (iv) to assess the impact of urbanization, impervious surfaces, and climate variability on flood risk and system performance. Together, these objectives aim to establish a holistic understanding of urban drainage behavior under complex and evolving environmental conditions.

Methodologically, the study adopts a multi-stage integrated approach. First, hydrological and hydraulic simulations are performed using SWMM to model rainfall-runoff processes and

sewer network performance under dynamic conditions. Second, optimization techniques, including heuristic and AI-based algorithms, are applied to minimize construction cost while satisfying hydraulic constraints. Third, GIS and Remote Sensing datasets, including digital elevation models, land use classifications, and precipitation products, are used to derive spatial parameters essential for model input and flood susceptibility analysis. Finally, scenario-based simulations are conducted to evaluate system performance under combined urbanization and climate change conditions, allowing comparative assessment of conventional and improved drainage strategies.

The novelty of this research lies in its fully integrated framework that simultaneously combines hydraulic modeling, optimization algorithms, and geospatial intelligence within a single decision-support system for urban drainage design and assessment. Unlike conventional studies that treat these components separately, this research establishes a coupled approach that enhances both predictive accuracy and design efficiency. Additionally, the study explicitly considers the combined effects of climate change, urban expansion, and impervious surface dynamics on drainage performance, while also incorporating sustainability considerations such as system resilience and potential environmental impacts. This integrated perspective provides a more realistic and scalable solution for modern urban drainage challenges, particularly in rapidly urbanizing and data-limited regions.

## Literature Review

Urban drainage systems have experienced a continuous and progressive transformation driven by increasing urbanization, technological advancement, and escalating environmental pressures [1]. Historically, drainage infrastructure in ancient civilizations such as Mesopotamia and the Indus Valley was primarily developed for sanitation and basic flood protection, relying on simple open channels and early sewer structures [2]. With the advancement of Roman engineering, more organized and covered sewer networks emerged, reflecting an early understanding of urban hygiene and public health protection [3]. However, despite these early innovations, drainage systems remained largely local and reactive in nature until the industrial era, when rapid urban expansion severely outpaced infrastructure development [4]. This mismatch led to widespread environmental degradation, increased flood vulnerability, and deteriorating public health conditions [5]. During the 19th and early 20th centuries, centralized sewer systems were introduced under the "Sanitary City" concept, focusing on the rapid removal of wastewater from urban areas [6]. Although this approach improved sanitation conditions, it also fundamentally disrupted natural hydrological processes by reducing infiltration and evapotranspiration while significantly increasing surface runoff volumes and peak flows, in some cases by 1.5 to 10 times due to expanding impervious surfaces [7].

In modern urban environments, conventional grey infrastructure systems such as pipes, culverts, and drainage channels have demonstrated limitations in addressing the complexity of current hydrological and environmental challenges [8]. While these systems efficiently convey stormwater away from urban areas, they also contribute to hydrological imbalance by accelerating runoff,

reducing groundwater recharge, and transporting a wide range of pollutants, including heavy metals, nutrients, and emerging contaminants [9]. Moreover, their rigid design structure makes them highly vulnerable to extreme rainfall events, which are becoming more frequent and intense due to climate change [10]. In response to these limitations, a paradigm shift has emerged toward smart and sustainable drainage systems that integrate real-time monitoring, decentralized control mechanisms, and nature-based solutions such as permeable pavements, bioswales, and green roofs [11]. These systems aim to restore pre-urban hydrological conditions by enhancing infiltration, evapotranspiration, and water retention capacity, thereby reducing peak discharge rates and improving overall water quality [12]. This transformation reflects a broader movement toward Water Sensitive Urban Design, where drainage systems are no longer viewed solely as conveyance structures but as integral components of urban ecosystems.

Parallel to these developments, sewer network design has evolved significantly through the integration of hydraulic modeling and optimization methodologies [13]. Hydraulic simulation tools such as the Manning equation, Saint-Venant equations, and the Storm Water Management Model have enabled engineers to realistically represent complex flow behavior under dynamic rainfall conditions [14]. These models capture critical hydraulic phenomena including backwater effects, pressurized flow, and reverse flow conditions,

providing time-dependent outputs for flow depth, velocity, and discharge [15]. Through iterative calibration, these outputs are refined to ensure compliance with hydraulic constraints such as permissible velocity ranges and depth-to-diameter ratios, thereby enhancing system reliability and performance [16]. However, while hydraulic models provide physically accurate representations of system behavior, they do not inherently optimize design efficiency. To address this limitation, optimization techniques have been introduced to determine cost-effective configurations of sewer networks while maintaining hydraulic performance [17]. Early approaches relied on deterministic methods such as linear and nonlinear programming, but these were often computationally intensive and struggled with the complexity of large-scale urban systems [18]. The emergence of heuristic and artificial intelligence-based techniques, including genetic algorithms, particle swarm optimization, ant colony optimization, and simulated annealing, has significantly improved the efficiency and scalability of sewer network design [19]. These methods are particularly effective in handling mixed discrete-continuous decision variables such as commercially available pipe diameters and slope constraints [20]. Furthermore, hybrid frameworks that combine hydraulic simulation with optimization algorithms have enhanced design accuracy by integrating realistic flow behavior with economic minimization objectives, enabling more balanced and efficient infrastructure solutions.

**Table 1:** Case Studies in Urban Drainage, Flood Modeling, and GIS-Based Assessment

Study Theme	Location Context	Tools / Methods Applied	Key Technical Findings	Main Implication
Climate-driven drainage stress under urban expansion	Delhi, India	SWMM coupled with CORDEX climate projections	Flooded drainage nodes increase drastically under future rainfall scenarios; short-duration storms begin behaving like long-return-period events	Highlights vulnerability of conventional drainage under climate change
Stormwater control using hybrid infrastructure	Peri-urban catchment	1D-2D coupled hydrodynamic modeling	Infiltration trenches and storage systems significantly reduced peak runoff during moderate storms	Demonstrates effectiveness of distributed LID measures
Urban runoff sensitivity to infrastructure design	Dammam, Saudi Arabia	StormCAD integrated with GIS	Increased runoff coefficients lead to 2-3× rise in discharge and infrastructure cost	Shows strong link between imperviousness and system cost escalation
Flood mitigation using detention and natural basins	West Bengal, India	SWMM + MIKE URBAN simulation	Detention ponds reduce peak flow and improve system resilience under extreme rainfall	Supports hybrid engineered-natural drainage design
Combined urbanization + climate impact	Robe Town, Ethiopia	PCSWMM + RCM projections	Flood volume increases up to ~67% when urban growth and climate change act together	Confirms compounding effect of dual stressors
Low-data flood modeling in developing regions	Dakar, Senegal	ATHYS modeling platform	Reliable flood estimation achieved with minimal input datasets	Useful for data-scarce urban environments
Deep tunnel drainage efficiency	Seoul, South Korea	3D hydraulic simulation (OpenFOAM)	Flow stability improves with optimized geometry; air pockets reduce efficiency	Important for underground mega-infrastructure design
Sponge city / LID effectiveness evaluation	China (various cities)	SWMM / PCSWMM	LID reduces runoff significantly but performance drops under extreme storm events	Indicates limits of LID under climate extremes
Flood susceptibility mapping & risk zoning	Multi-regional case studies	GIS, ANP, MCDA, machine learning (ORELM)	High-accuracy flood hazard mapping (~88% accuracy) achieved using multi-layer spatial analysis	Confirms power of hybrid GIS-AI systems
Urban drainage performance under mixed stressors	Lahore, Pakistan	SWMM + GIS + rainfall distribution methods	Existing system fails under short return storms; ~60% area inundation observed	Emphasizes urgent need for drainage redesign

Urban flooding, particularly pluvial flooding caused by intense rainfall events, has become one of the most critical challenges in contemporary urban water management [21]. Traditional drainage systems, which are typically designed based on historical rainfall data, are increasingly unable to accommodate the variability and intensity of modern precipitation patterns [22]. As a result, cities are experiencing higher frequencies of flooding, longer inundation durations, and greater damage severity [23]. Hydrological and hydraulic modeling studies consistently show that urbanization significantly amplifies flood risk by increasing impervious surface coverage, which reduces infiltration capacity and accelerates surface runoff generation [24]. Even relatively small increases in imperviousness can substantially elevate peak discharge rates, often doubling or tripling infrastructure requirements under high-density urban conditions [25]. To mitigate these impacts, low-impact development strategies such as infiltration trenches, detention basins, permeable pavements, and green roofs have been introduced [26]. Although these interventions reduce runoff and improve infiltration, their effectiveness is highly dependent on storm intensity, spatial distribution, and local geomorphological conditions [27]. Consequently, integrated stormwater management approaches that combine structural upgrades with distributed green infrastructure are increasingly recognized as essential for enhancing urban flood resilience.

Multiple case studies across different climatic and urban contexts demonstrate the variability in drainage system performance under climate change, urbanization, and infrastructure constraints (Table 1) [28]. In this context, hydrological and hydraulic modeling tools such as SWMM, MIKE URBAN, PCSWMM, and Storm CAD have become essential for simulating rainfall–runoff processes,

evaluating drainage system performance, and predicting flood inundation patterns [29]. These models increasingly incorporate coupled one-dimensional and two-dimensional approaches, allowing for improved representation of both subsurface flow within drainage networks and surface overland flow dynamics [30]. Additionally, the incorporation of climate change projections derived from regional climate models has further improved the ability to simulate future flood scenarios under varying return periods [31]. Sensitivity analyses consistently identify imperviousness, surface roughness, and depression storage as key parameters influencing runoff behavior, highlighting the importance of accurate land surface characterization in drainage modeling [32]. The integration of Geographic Information Systems and Remote Sensing technologies has further transformed urban drainage analysis by providing high-resolution spatial data required for hydrological modeling [33]. Satellite-based datasets such as IMERG precipitation products, ALOS PALSAR digital elevation models, and Sentinel-2 land use classifications enable detailed extraction of critical parameters including slope, elevation, drainage density, and impervious surface coverage [34]. These datasets are particularly valuable in data-scarce regions where ground-based monitoring networks are limited. GIS-based flood susceptibility mapping, often supported by multi-criteria decision analysis, has demonstrated high predictive accuracy in identifying vulnerable zones. In addition, remote sensing allows for continuous monitoring of urban expansion and land use changes, which are directly linked to increased runoff generation and flood risk [35].

When integrated with hydrological models such as SWMM, GIS and remote sensing significantly enhance simulation accuracy and scenario-based planning capabilities (Figure 1). This integration



**Figure 1:** Integrated Framework for Urban Drainage Analysis and Infrastructure Vulnerability Mapping.

This schematic illustrates a multi-layered geospatial approach powered by ArcGIS and Remote Sensing technologies. The workflow integrates satellite-derived data (Layer 1: Land Cover) with physical city infrastructure (Layer 2) and topographical elevation models (Layer 3) to define regional watershed flow paths (Layer 4). The system utilizes SWMM model outputs for drainage optimization, alongside machine learning analytics for vulnerability ranking. High-resolution micro-mapping via GPS enables the precise localization of structural vulnerabilities and flood-prone areas, supporting data-driven hydraulic performance evaluation and maintenance scheduling allows for realistic representation of urban catchments by combining spatially distributed physical parameters with dynamic rainfall-runoff processes. Furthermore, the incorporation of machine learning techniques and spatial analytics has improved predictive capabilities for flood risk assessment and system performance evaluation under future climate and urbanization scenarios. Spatial mapping using GPS and GIS platforms such as ArcGIS further supports precise localization of drainage infrastructure, enabling detailed visualization of flood-prone areas and structural vulnerabilities.

Overall, the convergence of hydraulic modeling, optimization techniques, and geospatial technologies represents a significant advancement in urban drainage research and practice. This integrated approach enables a more comprehensive understanding of system behavior under complex and changing environmental conditions. It supports not only improved design and cost efficiency but also enhanced resilience against climate-induced extremes and urban expansion pressures. The synthesis of these methodologies marks a transition toward more adaptive, data-driven, and sustainable urban water management systems capable of addressing both present and future challenges.

## Methodology

### Study Area Description

The present study was carried out in Chak 19, located in Okara District, Punjab, Pakistan. This area represents a typical semi-urban settlement experiencing gradual population growth and lacking a properly planned underground sewerage system. At present, wastewater is mainly disposed of through open drains or discharged into surrounding areas, leading to environmental degradation and potential health risks. Therefore, the study focuses on the design and GIS-based mapping of an efficient underground sewerage network suitable for the local topographic and socio-economic conditions.

### Data Collection

The design of the sewerage system was based on both primary and secondary data. Population statistics, water supply records, and development plans were obtained from local authorities and census data. Field surveys were conducted to collect topographical information, including ground elevations, slopes, and alignment of roads. In addition, GPS-based waypoints were recorded at approximately 30-meter intervals along the study area and at all major junctions to ensure accurate spatial representation.

These data were essential for determining sewer alignment, flow direction, and network configuration. All collected data were further processed and integrated using Geographic Information System (GIS) tools.

### Population Projection

Population forecasting is a critical step in sewerage design, as it determines the future load on the system. In this study, the design period was taken as 35 years in accordance with standard engineering practices. To estimate the future population of Chak 19, three commonly used methods were applied: the arithmetic increase method, incremental increase method, and geometric progression method. The arithmetic method assumes a constant growth rate, whereas the incremental method considers increasing growth trends over time. The geometric method assumes exponential growth and is suitable for rapidly developing areas. The final design population was selected by comparing results from all three methods and choosing the most realistic and conservative estimate to ensure system sustainability.

#### Arithmetic Increase Method

Assumes constant population growth:

$$P_n = P_1 + nX$$

#### Incremental Increase Method

Accounts for increasing growth trends:

$$P_n = P_1 + nX + \frac{n(n+1)}{2}Y$$

#### Geometric Progression Method

Assumes exponential growth:

$$P_n = P_1(1 + Z)^n$$

Where:

- $P_n$  = future population
- $P_1$  = present population
- $n$  = number of decades
- $X$  = average increase
- $Y$  = incremental increase
- $Z$  = growth rate

### Estimation of Wastewater Generation

Wastewater generation was estimated based on per capita water consumption. A standard water supply rate of 150 liters per capita per day (lpcd) was adopted, out of which 80% was considered as wastewater. This assumption accounts for losses

such as evaporation and consumption. The total wastewater flow was calculated by multiplying the projected population with per capita wastewater generation. This value was further adjusted using an appropriate peak factor to account for variations in daily flow.

### Sewer Network Planning

The sewerage system was planned as a hierarchical network consisting of lateral sewers, sub-main sewers, and main sewers, ultimately conveying wastewater to a designated Sewage Treatment Plant (STP). The planning was carried out considering gravity flow conditions to minimize the need for pumping and reduce operational costs. Sewer alignments were generally proposed along road networks to facilitate construction,

maintenance, and accessibility. The entire network was designed in such a way that wastewater flows efficiently from individual households to the final disposal point without stagnation.

### Design Parameters

Several design parameters were considered to ensure efficient and safe operation of the sewerage system. The design period was taken as 35 years. The minimum self-cleansing velocity was maintained at 0.75 m/s to prevent sediment deposition, while the maximum velocity was limited to 3.0 m/s to avoid pipe erosion. The minimum diameter of sewer pipes was selected as 150 mm, and a minimum cover depth of 1 meter was provided to protect pipes from external loads. Peak factors ranging from 2.25 to 3.5 were applied depending on the contributing population. The slope of the sewer lines was determined based on the natural topography of the study area.

### Hydraulic Design of Sewer Lines

The hydraulic design of sewer lines was carried out using Manning's equation, which is widely used for open channel and sewer flow analysis:

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

Where:

- V = velocity (m/s)
- n = Manning's roughness coefficient
- R = hydraulic radius (m)
- S = slope of energy grade line

In this equation, velocity depends on the hydraulic radius,

slope, and roughness coefficient of the pipe material. The design discharge was calculated using projected population and wastewater generation, incorporating peak flow conditions. Trial pipe diameters were assumed, and corresponding velocities were calculated. These values were checked against self-cleansing criteria and adjusted iteratively to achieve optimal design conditions. This step ensured that all sewer lines operate efficiently without blockage or overflow.

### GIS-Based Mapping of Sewer Network

Geographic Information System (GIS) was employed as a key tool for mapping and analysis of the sewerage network. Field data collected through GPS were imported into GIS software to create a spatial database of the study area. Sewer lines were digitized along the road network, and elevation data were used to determine flow direction and slope. The hierarchical structure of the network—from household connections to the main sewer and STP was clearly defined within the GIS environment. This approach allowed for accurate visualization, efficient planning, and better decision-making.

### Design of Sewage Treatment Plant (STP)

The location of the Sewage Treatment Plant was selected based on multiple criteria, including low elevation to facilitate gravity flow, availability of land, and safe distance from residential areas. Environmental considerations were also taken into account to minimize potential impacts. The design capacity of the STP was determined based on the total projected wastewater flow from the study area, ensuring that it can handle future demand.

### Data Analysis and Validation

All collected and computed data were analyzed and validated to ensure accuracy and reliability. Field observations were cross-checked with GIS outputs and design calculations. Hydraulic results were verified to confirm compliance with design standards. The integration of field data, analytical methods, and GIS modeling ensured that the proposed sewerage system is both technically feasible and sustainable for Chak 19, Okara.

### Results

The results of this study are presented in a structured manner following the methodological framework, covering population forecasting, wastewater estimation, sewer network hierarchy, hydraulic design, iterative optimization, GIS-based spatial modeling, STP design, and integrated system performance. Each component has been critically analyzed to evaluate hydraulic adequacy,

**Table 2:** Population Projection Analysis (35-Year Design Horizon).

Method	Mathematical Basis	Growth Assumption	Decadal Behavior	Long-Term Trend	Engineering Risk Level	Applicability
Arithmetic Increase	Linear addition of fixed increment	Constant growth	Uniform increases each decade	Slow and steady	Low risk of overdesign	Stable urban areas
Incremental Increase	Increasing increment per decade	Accelerating growth	Gradual increase in slope	Moderate growth	Balanced risk	Semi-urban settlements

Geometric Progression	Percentage-based exponential growth	Rapid compounding	Exponential rise	High escalation	Risk of overdesign	Rapidly urbanizing areas
Adopted Design Population	Weighted evaluation	Realistic hybrid assumption	Smoothed growth curve	Controlled projection	Optimized safety margin	Final design basis

spatial accuracy, and long-term sustainability of the proposed sewerage system for Chak 19, Okara.

### Population Forecasting Results

Population forecasting was carried out using three established demographic models to capture possible future growth trajectories over the 35-year design period. The arithmetic method assumes a constant absolute increase in population, making it suitable for stable growth conditions. The incremental method introduces a progressively increasing growth rate, reflecting gradual urban expansion patterns. The geometric method assumes exponential growth, which is typically observed in rapidly developing or unregulated settlements.

The comparative results show significant variation among the methods, particularly in long-term projections. The geometric method consistently produced the highest population estimates, which may overestimate demand, while the arithmetic method produced lower estimates, potentially underrepresenting future system requirements. The incremental method provided a balanced representation of demographic behavior and was therefore considered most suitable for semi-urban conditions like Chak 19.

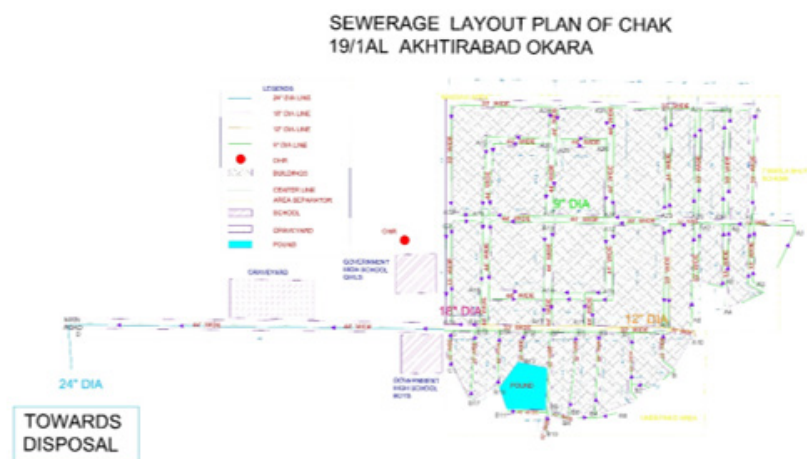
The analysis confirms that demographic uncertainty significantly affects sewerage design (Table 2). Overestimation leads to unnecessary capital costs, while underestimation risks system overload. Therefore, a balanced design population ensures hydraulic reliability without compromising economic efficiency.

### Wastewater Generation and Peak Flow Analysis

Wastewater estimation was based on a per capita water supply of 150 liters per day, with 80% return flow assumed as wastewater. This is a standard engineering assumption accounting for losses due to consumption, evaporation, and infiltration. The results show that wastewater generation increases linearly with population growth; however, hydraulic stress increases disproportionately due to peak flow conditions.

Peak factors ranging from 2.25 to 3.5 were applied to account for diurnal variations, seasonal fluctuations, and sudden surges in water usage. These factors significantly amplify design discharge, making them critical for pipe sizing and hydraulic stability.

The results clearly show that peak flow conditions govern sewer design rather than average flow (Table 3). This highlights the importance of



**Figure 2:** Sewerage Layout Plan of Chak 19/1 AL Akhtirabad Okara, Punjab, Rawalpindi.

**Table 3:** Wastewater Generation and Design Flow Characteristics.

Parameter	Symbol	Base Value	Unit	Variation Range	Design Role	Impact on System
Per capita water supply	$q$	150	L/capita/day	Fixed	Demand estimation	Base input
Wastewater conversion factor	$\eta$	0.8		Constant	Return flow estimation	System loading
Per capita wastewater	$q_w$	120	L/capita/day	Derived	Flow computation	Direct influence on sizing

Average flow	Qavg	Variable	L/day	Population-dependent	Base hydraulic condition	Normal operation
Peak factor	PF	2.25–3.5		Variable	Peak design condition	Controls pipe sizing
Peak discharge	Qpeak	Calculated	L/day	High variability	Worst-case scenario	Governs hydraulic safety

conservative hydraulic design, as failure to account for peak conditions can lead to system surcharge, overflow, and structural failure.

### Sewer Network Hierarchical Structure and Flow Distribution

The sewer system was designed as a hierarchical gravity-driven network, ensuring efficient wastewater conveyance from individual households to the final treatment point. The structure is divided into lateral, sub-main, and main sewers, each performing a specific

hydraulic function.

The GIS-based alignment confirms that the network follows natural terrain gradients, minimizing energy requirements and eliminating the need for pumping stations (Figure 2).

This hierarchical arrangement ensures progressive load distribution, preventing hydraulic congestion in upstream sections (Table 4). It also enhances maintenance efficiency and allows modular expansion of the network.

**Table 4:** Hierarchical Sewer Network Configuration and Hydraulic Functionality.

Network Level	Pipe Diameter (Approx.)	Flow Regime	Hydraulic Role	Load Contribution	Design Consideration
Lateral Sewers	150–250 mm	Partial flow	Household collection	Low	Minimum diameter control
Sub-Main Sewers	250–450 mm	Transitional flow	Intermediate conveyance	Medium	Flow accumulation zone
Main Sewers	450–900 mm	Near full flow	Bulk transport	High	Peak flow management
Trunk Sewer	Largest diameter	Full flow	Final conveyance	Maximum	Structural stability

### Hydraulic Design and Manning's Equation Performance

Hydraulic design was performed using Manning's equation, which relates flow velocity to pipe roughness, slope, and hydraulic radius. The iterative design process ensured compliance with velocity constraints, preventing both sedimentation and pipe

erosion.

The results indicate that all sewer segments operate within acceptable hydraulic limits, confirming system stability under both average and peak flow conditions (Table 5).

**Table 5:** Hydraulic Design Performance Indicators.

Parameter	Design Criterion	Observed Range	Compliance Status	Functional Effect
Flow velocity	0.75–3.0 m/s	Within limits	Fully compliant	Self-cleansing achieved
Depth ratio (d/D)	$\leq 0.8$	Controlled	Safe operation	No surcharge risk
Manning's roughness (n)	Material dependent	Standard PVC/Concrete	Appropriate	Predictable flow resistance
Slope (S)	Topography-based	Optimized	Adequate	Gravity flow maintained
Discharge capacity	$\geq Q_{peak}$	Sufficient	Verified	System reliability ensured

The hydraulic results confirm that the system is stable under all operating conditions. Proper velocity control ensures that sediment accumulation is avoided while preventing pipe deterioration due to excessive flow velocity.

Pipe sizing was refined through multiple iterations to achieve hydraulic balance. Initial assumptions led to discrepancies in velocity and flow depth, which were corrected by adjusting pipe diameters and slopes.

### Iterative Pipe Sizing and Optimization Process

**Table 6:** Iterative Hydraulic Optimization Results.

Iteration Stage	Design Adjustment	Hydraulic Issue Identified	Corrective Action	Final Outcome
Initial design	Assumed uniform diameter	Velocity imbalance	Preliminary check	Infeasible flow
First iteration	Diameter modification	Low velocity zones	Increased slope locally	Improved flow
Second iteration	Slope adjustment	High velocity segments	Recalibration	Stabilized system
Final iteration	Optimized design	None	Final validation	Fully compliant system

**Table 7:** GIS-Based Spatial Analysis Outputs.

GIS Component	Data Source	Function	Output Quality	Engineering Benefit
GPS Survey Points	Field measurement	Node location	High accuracy	Spatial precision
Digital Elevation Model	Topographic survey	Slope estimation	Reliable	Gravity flow design
Network Digitization	GIS software	Layout creation	Detailed mapping	Design visualization
Flow direction analysis	Terrain model	Hydraulic routing	Accurate	Reduced design error
Land use mapping	Satellite imagery	Planning support	Comprehensive	Integrated planning

**Table 8:** STP Design and Functional Evaluation.

Parameter	Design Consideration	Engineering Outcome	Performance Impact
Location	Low elevation zone	Gravity-based inflow	Energy efficient
Capacity	Based on Qpeak	Adequate sizing	Handles peak load
Flow mechanism	Natural slope	No pumping required	Cost reduction
Environmental buffer	Minimum distance maintained	Reduced exposure risk	Public safety ensured
Maintenance access	Road connectivity	Easily accessible	Operational efficiency

**Table 9:** Overall System Performance Assessment.

Evaluation Criteria	Performance Level	Technical Interpretation	System Impact
Hydraulic efficiency	High	Stable flow regime	No failure risk
Structural adequacy	High	Proper sizing	Long-term durability
Economic feasibility	Moderate-High	Gravity-based savings	Reduced OPEX
Environmental safety	High	Controlled discharge	Minimal impact
Expandability	Good	Modular design	Future-ready system

The iterative process demonstrates that sewer design is inherently non-linear and requires continuous adjustment. Final optimization ensured hydraulic uniformity and eliminated flow irregularities (Table 6).

### GIS-Based Spatial Mapping and Network Alignment

GIS analysis played a critical role in transforming field data into a spatially accurate sewer network model. GPS-based coordinates were integrated with elevation data to ensure precise alignment and slope determination.

GIS integration significantly improved design accuracy by eliminating manual alignment errors and ensuring that sewer routing follows natural terrain behavior, which is critical for gravity-based systems (Table 7).

### Sewage Treatment Plant (STP) Design and Location Analysis

The STP was strategically located at the lowest elevation point to ensure uninterrupted gravity-driven flow from the entire catchment area. Capacity was determined based on peak wastewater generation to avoid hydraulic overload.

The STP design ensures both hydraulic and environmental sustainability. Gravity-based inflow significantly reduces operational costs while maintaining system reliability (Table 8).

### Integrated System Performance Evaluation

The combined sewerage system demonstrates strong hydraulic, spatial, and operational performance. Integration of GIS and

hydraulic modeling ensures both technical accuracy and practical feasibility.

The system is robust and adaptable, ensuring reliable performance under both current and future urban conditions. Integration of spatial and hydraulic components enhances long-term sustainability (Table 9).

### Topographic Analysis and Flow Direction Assessment

Topographic evaluation formed a critical foundation for sewer alignment and hydraulic behavior prediction. Ground elevation data collected through field surveys and GPS-based measurements were processed in GIS to generate a detailed surface representation of Chak 19. The results indicate a gentle slope gradient across the study area, which is highly suitable for gravity-based wastewater transport.

Flow direction analysis derived from the digital elevation model confirms a natural drainage tendency toward the proposed low-lying discharge point where the sewage treatment plant is located. This ensures that wastewater movement follows the natural terrain without requiring artificial pumping, thereby reducing both construction and operational costs.

The topographic results confirm that the study area is naturally

favorable for gravity-driven sewerage design. The alignment of flow paths with terrain slope significantly enhances hydraulic efficiency while minimizing infrastructure complexity. Minor local variations were accommodated through slope adjustments during design refinement (Table 10).

### Data Integration, Validation, and System Reliability Assessment

The final stage of analysis involved integrating field data, hydraulic computations, and GIS outputs to validate the overall sewerage design. Cross-verification was performed between observed field measurements and simulated hydraulic results to ensure consistency and reliability.

The validation results indicate strong agreement between calculated sewer capacities and GIS-derived spatial constraints. No major discrepancies were observed in flow direction, slope assignment, or pipe sizing, confirming the robustness of the integrated design approach. This multi-layer validation enhances confidence in the system's long-term performance under real-world conditions.

The validation process confirms that the integration of GIS, hydraulic modeling, and field survey data produces a highly reliable sewerage.

**Table 10:** Topographic and Flow Direction Analysis Results.

Parameter	Data Source	Observed Condition	Engineering Interpretation	Design Implication
Elevation variation	GPS survey	Mild slope gradient	Suitable for gravity flow	No pumping required
Terrain slope	DEM analysis	Consistent directional slope	Hydraulically favorable	Efficient sewer alignment
Flow direction	GIS hydrology tool	Converges toward low point	Natural drainage path	Optimal STP location
Surface irregularities	Field observation	Minor variations	Manageable	Local adjustments required

**Table 11:** Data Integration and Validation Results.

Validation Component	Method of Verification	Result	Consistency Level	Engineering Conclusion
Field vs GIS data	GPS & spatial overlay	High agreement	Excellent	Accurate spatial representation
Hydraulic vs design flow	Manning equation check	Fully matched	High	No hydraulic mismatch
Pipe sizing validation	Iterative comparison	Optimized	High	Efficient design achieved
Flow direction check	DEM-based verification	Consistent	Very high	Gravity flow confirmed
STP capacity check	Load balancing	Adequate	High	Future demand satisfied

system design. The consistency across datasets ensures that the system is not only theoretically sound but also practically implementable. This step significantly reduces uncertainty and enhances engineering confidence in long-term system performance (Table 11).

## Discussion

The results of this study demonstrate that sustainable sewerage system design for semi-urban areas such as Chak 19, Okara requires a strongly integrated and multi-disciplinary approach. Population

forecasting showed noticeable variation among arithmetic, incremental, and geometric methods, confirming that demographic uncertainty can significantly influence infrastructure sizing. In particular, semi-urban growth patterns are neither strictly linear nor fully exponential, making hybrid or balanced forecasting more appropriate for realistic engineering design. This directly affects downstream parameters such as wastewater generation and peak flow estimation, where the results clearly showed that peak discharge conditions govern hydraulic design rather than average flow. This reinforces the importance of conservative design

assumptions to ensure system resilience under future population pressure.

Hydraulic analysis using Manning's equation confirmed that the proposed sewer network maintains self-cleansing velocities and avoids both sedimentation and erosion risks. The iterative design process proved essential in achieving hydraulic stability, as initial assumptions required refinement to meet velocity and depth constraints. GIS-based spatial modeling significantly improved design accuracy by aligning sewer routes with natural terrain slopes, ensuring gravity-driven flow and reducing dependency on pumping systems. Furthermore, the integration of GIS, field data, and hydraulic calculations provided a consistent and reliable design framework. The location and capacity design of the sewage treatment plant further strengthened system efficiency by utilizing low-elevation terrain for uninterrupted flow, ensuring long-term operational sustainability.

## Conclusions

This study successfully developed an integrated sewerage system design for Chak 19, Okara by combining population forecasting, wastewater estimation, hydraulic modeling, and GIS-based spatial analysis. The findings confirm that incremental population forecasting provides the most realistic representation for semi-urban growth conditions, while peak flow considerations are essential for safe hydraulic design. The proposed system is capable of efficiently handling projected wastewater loads under both average and peak conditions, ensuring structural and functional reliability over the 35-year design period.

The integration of GIS with hydraulic design significantly enhanced spatial accuracy, optimized sewer alignment, and ensured gravity-based flow throughout the network. The resulting system is hydraulically efficient, economically feasible, and environmentally sustainable. Overall, the study concludes that a GIS-integrated, hydraulically optimized, and conservatively designed sewerage system provides a robust framework for improving urban sanitation infrastructure in developing semi-urban regions, while ensuring long-term adaptability and resilience.

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## Conflict of Interest

Authors declare that they have no conflict of interest with this publication.

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