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Modeling and Evaluation of Sanliurfa Province Hilvan District Wastewater Treatment Plant with Hardy-Cross Method and GIS Supported AHP Method

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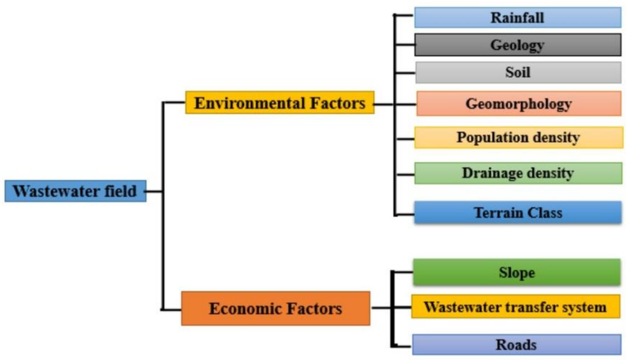
Graphical abstract



Abstract

Ensuring an adequate supply of water with acceptable quality is a fundamental objective of water and wastewater management systems; however, it also poses significant technical and operational challenges. Limited data on water quality, quantity, and infrastructure conditions, together with various environmental factors that can affect system performance, make risk assessment in water distribution and wastewater networks critically important. The main objective of this study is to develop an optimal solution approach for the sustainable operation and management of the wastewater treatment system in the Hilvan District of Şanlıurfa Province, in response to increasing population and water demand. Within this scope, the hydraulic behavior of the system was analyzed using the Hardy-Cross method, and the flow–pressure balance was modeled. The obtained hydraulic data were integrated with a Geographic Information System (GIS)-based Analytic Hierarchy Process (AHP) to establish a spatial decision support system. Environmental factors (precipitation, land use, geology, geomorphology, and protected areas) and economic factors (slope, wastewater transfer lines, and land value) were evaluated, and suitability weights were assigned to each. As a result, the integration of hydraulic analyses derived from the Hardy-Cross model with the GIS-AHP method enabled the identification of spatial suitability distributions for wastewater treatment sites, leading to optimized system performance. This integrated approach provides an effective decision support framework for similar water and wastewater management projects.

Keywords: AHP Method, Environmental Management, GIS Technique, Wastewater Treatment Zone

1. Introduction

Wastewater management is a critical component of urban infrastructure, both environmentally and socially. Rapid population growth, unplanned urbanization, and limited natural resources challenge the effective operation of urban wastewater systems and contribute to environmental problems. In particular, the prevalence of impervious surfaces such as roads, roofs, and parking lots disrupts the natural water cycle, leading to the contamination of surface and groundwater resources (Ucuncu 2022). These challenges highlight the necessity of adopting systematic and integrated approaches in urban infrastructure planning.

The design and operation of wastewater treatment plants are vital for ensuring the sustainability of urban life. Although traditional hydraulic calculation methods (Dead Point Method, Hardy-Cross Method, Equivalent Pipe Method, etc.) provide guidance for pipe sizing and flow optimization, inappropriate pipe diameter selection can increase costs and reduce system efficiency (Kinik & Aykac 2021). Moreover, spatial decisions such as treatment plant location, if made without considering environmental, economic, and infrastructural criteria, may lead to both technical and environmental problems.

The world's rapidly growing population and increasing needs and expectations lead to uncontrolled consumption of limited resources, a constant increase in the type and amount of waste resulting from consumption, unplanned urbanization and land use problems. This situation causes negative effects that threaten both the environment and public health. The main problems encountered as a result of poor waste management are air pollution, water pollution, soil pollution, economic losses and negative effects on quality of life. Waste management is a necessity to eliminate the problems caused by waste. In order to manage waste effectively, it is important to consider the natural, economic and social elements affecting waste management with an interdisciplinary approach (Ćetković*et al.* 2023; Agacsapan 2016).

There are many particularly impermeable surface areas (roads, parking areas, roofs) in the architectural layouts of cities (roads, parking areas, roof systems, etc.). This sealing negatively affects the natural flow system of rainfall and the sewage system hydraulically. Such water cycle changes prevent the nutrition of underground and surface water resources and pollute the environment. Rainwater that accumulates on the surface and does not leak into the groundwater becomes polluted during its stay on the surface and subsequently pollutes groundwater and surface water reserves. It emphasizes the necessity of addressing urban infrastructure systems with an increasingly integrated approach (Ucuncu 2022).

Nowadays, waste management has become an important issue that needs to be addressed interdisciplinary. Increasing population and developing industry, as well as limited natural resources, make waste management more important day by day. In this section, general information about waste management is discussed. The development process of waste management, which emerged when waste became a problem, what waste is and types of waste, the purposes and basic principles of waste management, and the problems encountered in the implementation process of waste management should be discussed (Birpinar and Tugac 2021).

Wastewater treatment technology is basically based on physical, chemical and biological treatment processes. However, these processes are inferior to new treatment technologies because their operating costs are high, their efficiency for wastewater is not high, and they are not applied in practice. In recent years, there has been increasing interest in the use of electrochemical technologies in wastewater treatment (Benáková *et al.* 2018; Abdelmagid, *et al.* 2024; Katal and Pahlavanzadeh 2011). The chemicals contained in wastewater make it conductive and enable it to be stored in accordance with the electrochemical process (Camcioglu *et al.* 2015).

The motivation of this study is to provide a technically efficient and spatially suitable planning framework for the wastewater treatment plant in the Hilvan district. By integrating classical engineering approaches with decision support systems, the study seeks to offer sustainable and practically applicable solutions. Accordingly, this research models and evaluates the Hilvan Wastewater Treatment Plant through two complementary approaches: 1. The Hardy-Cross Method for hydraulic analysis and flow balancing in pipelines and sewer systems, 2. A GIS-supported AHP Method for multi-criteria decision-making in optimizing the plant location.

The study focuses on: Enhancing the design and operational efficiency of pipeline and pump systems, determining optimal plant locations based on environmental and economic parameters, Providing an integrated planning perspective through the combination of hydraulic and spatial analyses. Overall, hydraulic analysis and spatial evaluation will be performed for the Hilvan Wastewater Treatment Plant. The findings are expected to guide engineering practices and assist local authorities in making technically sound and environmentally appropriate wastewater management decisions.

1.1. Related Work

Previous studies evaluating wastewater treatment plant planning and sewer network hydraulics have commonly employed the Hardy–Cross method, GIS-based spatial analysis, and multi-criteria decision-making techniques such as AHP. Although the Hardy–Cross method is widely used for balancing flow in looped networks, it has several limitations, including sensitivity to initial flow estimations, slow convergence in complex systems, and the need for manual iteration, which can introduce calculation errors (Maruthai *et al.* 2025).

Similarly, GIS–AHP–based site selection studies are effective in integrating spatial and environmental factors; however, their limitations include dependency on expert judgment, subjective weighting of criteria, and sensitivity to changes in pairwise comparisons (Selvanarayanan *et al.* 2024).

In addition, many previous studies consider hydraulic and spatial components separately, which reduces the ability to capture interactions between network design, topography, and environmental constraints. This study addresses these gaps by integrating Hardy–Cross hydraulic modeling with GIS-supported AHP analysis within a unified decision-making framework for the Hilvan district.

2. Materials and Method

2.1. Study Area

Located in the northern part of Şanlıurfa province in southeastern Turkey, Hilvan District covers an area of approximately 1,278 square kilometers and is situated at an elevation of 600 meters above sea level. The region's geological structure is composed of formations from the Quaternary, Lower Miocene, Upper Miocene, and Eocene periods. Additionally, weathered carbonate rocks are prevalent across the area. Basaltic landforms dating back to the Upper Miocene period are particularly notable. The study area location map is shown in **Figure 1**.

Climate is one of the most significant natural factors affecting human activities in Hilvan. The district experiences extremely high temperatures during the summer months, which intensifies evaporation rates and adversely affects agricultural productivity. The regional economy is largely based on agriculture and livestock breeding, with key crops including wheat, lentils, maize, and cotton.

Geographically, Hilvan lies at approximately 37°N latitude and 38°E longitude. The district spans across two distinct plateaus: the Şanlıurfa-Bozova (calcareous) Plateau to the west, southwest, and south, and the Siverek-Viranşehir (basaltic) Plateau to the north and northeast. The western part of the basin features younger rock formations, characterized by rocky and hilly terrain. Furthermore, sedimentary carbonate rocks originating from the Upper Cretaceous to Paleocene periods are present throughout the district.

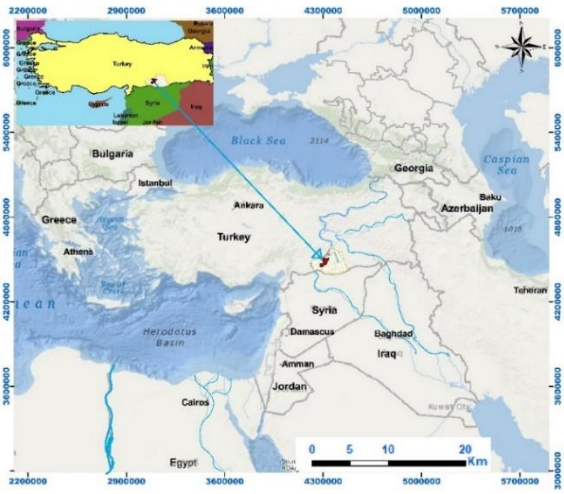


Figure 1. Location map of the study area (Hilvan).

The most significant water body in Hilvan is the Atatürk Dam reservoir, which is constructed on the Euphrates River. In addition, the Korçik and Şabo Streams flow seasonally and contribute to the district's limited surface water resources. Based on regional climatic data, the highest recorded daily temperature reaches up to 38.8°C in July, while the lowest temperature, typically observed in January, can drop to -1.3°C. The average annual precipitation is approximately 456.23 mm, classifying the area under a semi-arid climate regime (Akbiyik and Cakir 2023).

2.2. Material

In this study, the Hardy–Cross method and a GIS-based Analytic Hierarchy Process (AHP) were integrated to model and evaluate the planning, hydraulic design, and site selection processes for the wastewater treatment plant. The modeling activities were conducted within the boundaries of the Hilvan district of Şanlıurfa, selected due to its increasing population density, rising wastewater generation from agricultural activities, and growing rural infrastructure needs.

The primary datasets used in this study include:

Digital Elevation Model (DEM) data (30 m resolution), Geological maps obtained from the General Directorate of Mineral Research and Exploration (MTA) and local municipal authorities,

Land use and land cover (LU) data, Hydrological network and drainage maps, Climatic data for the Hilvan district provided by the Turkish State Meteorological Service, Settlement distribution, road networks, and existing infrastructure datasets obtained from local governmental institutions.

2.3. Dataset Access and Availability

Most of the datasets used in this study were obtained directly from official Turkish governmental institutions and local authorities and are not publicly accessible. These datasets include geology maps, settlement and infrastructure layers, and climate records, which were provided for academic use upon formal request.

DEM and land use datasets were obtained from publicly available national geospatial platforms.

Due to institutional confidentiality and data-sharing restrictions, the full dataset cannot be shared publicly. However, metadata descriptions and derived geospatial layers used in the analysis can be provided upon reasonable request to the corresponding author.

All spatial datasets used in the site selection analysis were integrated into a multi-criteria decision-making framework. Expert opinions were consulted in the determination of evaluation criteria, and criterion weights were assigned using the AHP methodology.

The scheme suitable for the hierarchical model of the wastewater treatment system for the Hilvan basin of Şanlıurfa province is given in **Figure 2**.

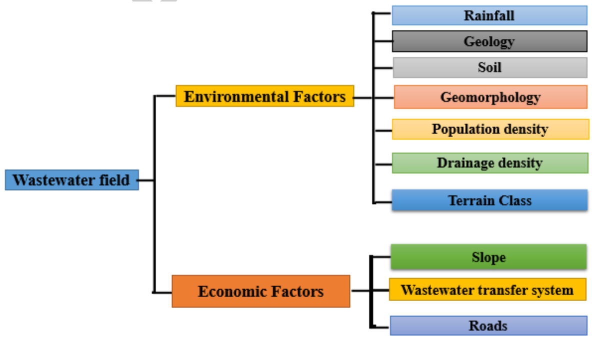


Figure 2. Scheme suitable for hierarchical model of wastewater treatment system (Aslan 2023).

Figure 3 shows the closed eyes network diagram for the study area.

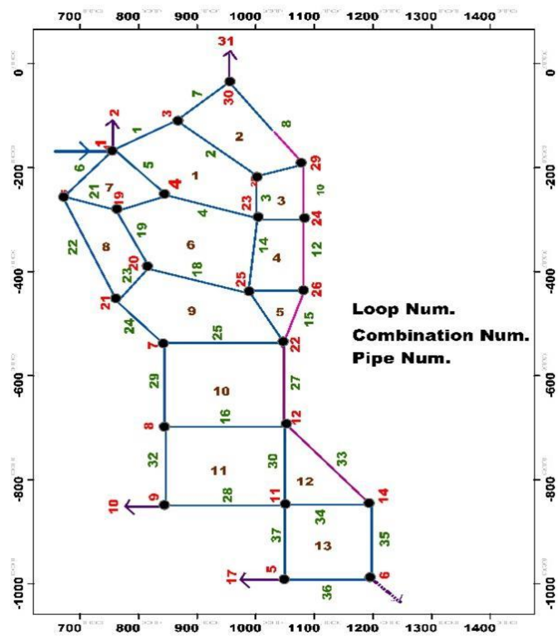


Figure 3. Closed eyes network diagram (Kocaman 2022)

2.4. Method

- **Spatial Data Processing:**

In the first phase of the study, basic spatial parameters such as sewer pipe lengths, surface elevations, and ground levels at designated manhole covers were extracted using ArcGIS 10.8 software. These data were supplemented with statistical projections of the study area's topography, population growth trends, water consumption rates, and wastewater production.

A comprehensive geographic model of the region was created by integrating environmental and physical parameters such as precipitation, slope, soil type, land use, geological structure, and geomorphological features. These parameters were selected based on their relevance to hydraulic modeling, infrastructure design, and the environmental suitability of treatment facilities (Naeemah Bashara and Qaderi 2024; Denysiuk *et al.* 2018).

- **Hydraulic Modeling Approach**

– **Application of the Hardy-Cross Method**

The Hardy-Cross method was used to calculate flow distribution and balance line losses in the sewer network. This method is an iterative approach used to balance energy losses in closed-loop piping systems. Initially, estimated flow rates were assigned to each line, and then the total head losses in the loop were calculated.

– **Execution of Hydraulic Calculations**

Hydraulic calculations were carried out using an Excel-based model. Line losses, slope, roughness coefficients, and flow rates were defined in formula-based cells using the Darcy-Weisbach and Hazen-Williams equations in the Excel environment.

The Hardy-Cross method was applied at each iteration step, and the resulting correction amounts were tracked in a tabular format. This allowed for transparent control of the calculation process and direct observation of the effects of parameter changes on the network.

The reason for preferring the Excel model over software-based simulations is to preserve the manual verifiability of the calculation process and methodological clarity.

- **AHP and GIS Integration**

The Analytical Hierarchy Process (AHP) was used to determine the relative importance of criteria for the study area. Criteria such as slope, soil type, distance to residential areas, geological structure, distance to water bodies, and land use were evaluated using a pairwise comparison matrix method, and weighting coefficients were calculated to maintain a consistency ratio (CR) below 0.1.

The weights obtained from the AHP were integrated onto the raster data in ArcGIS using the Weighted Overlay method. Alternatively, AHP weights were assigned to each criterion raster using the Raster Calculator and the following expression was used:

- **Methodological Workflow**

The general flow of the methodology is summarized in **Figure 2**. **Figure 2** Hilvan Region Wastewater Treatment System Integrated Modeling Workflow;

- Data Collection: Providing topographic, demographic, and infrastructure data
- GIS Analysis: Spatial extraction of slope, manhole location, and pipeline network
- Hydraulic Modeling: Network balancing using Excel-based Hardy-Cross iterations
- AHP Analysis: Calculating criteria weights and checking consistency
- GIS Integration: Creating a suitability map with a Weighted Overlay/Raster Calculator
- Result: Treatment plant layout and infrastructure planning recommendations

This diagram strengthens methodological transparency by visually summarizing the logical process of the study.

2.4.1. Hardy-Cross Method

Hardy-Cross (1936) was the first to make a systematic solution of steady flows in pipes. The reason why this method has a wide application area is that it is a method suitable for both manual and computer solution. Eryuruk (2021) conducted a study on the comparison of Equivalent Pipe and Hardy-Cross Methods. Tongur (2001) compared traditional and computerized pipe network analysis methods. Hodges *et al.* (2016) gave Mathcad applications of analysis and solutions of serial, parallel and networked pipe systems (Cross 1936; Er Yuruk 2021; Tongur 2021; Hodge *et al.* 2016).

It is generally not possible to tell at first glance which way water comes to any pipe of the work area network, because the flow rate in network networks can reach a point in various ways. Although it is a complicated flow in terms of analysis, the continuity and energy equations, which are the basic equations for network networks, can be written as follows:

- The flow coming into the junction is equal to the flow leaving the junction ($\Sigma Q=0$).
- The algebraic sum of load losses calculated in the same direction throughout any closed circuit is zero ($\Sigma jL=0$).

Because network networks are complex, analytical solutions are difficult. Hardy-Cross suggested the step-by-step approach method as a practical method. The principle of application of this method is summarized below:

- A reasonable current distribution is selected to satisfy the condition ($\Sigma Q=0$).
- For each pipe, hL = KQn head loss is written.

The K value is fixed for each pipe. For any pipe, from the Darcy-Weisbach relation

$J = b(Q^2/D^5)$ can be obtained. Accordingly, for D = Di and L = Li, $h_L = J_L = bQ^2/D^5 \, Li = KQ^2$. Accordingly, n = 2.

- By taking the load losses in the direction of the clockwise rotation as positive and negative in the other direction, the algebraic sum of the load losses for closed circuits is calculated ($\Sigma h_L = \Sigma KQ^n$). The fact that $\Sigma h_L = 0$ on the first try shows that we are very lucky. The number of iterations while balancing flow rates can be around 20; However, this depends entirely on the shape of the network and the accuracy of the selected current distribution (Jha and Mishra 2020).

- If the total load loss is different from zero (for $\Sigma h_L \neq 0$), the current in each closed circuit is rearranged with the correction flow rate ΔQ to try to ensure $\Sigma h_L = \Sigma KQ^n = 0$.

2.3.1.1 Calculation of ΔQ Correction Flow Rates

The head loss for each pipe, denoted as $K = b\frac{Q^n}{D^5}$, is calculated using the parameter *K*, where "b" is a constant, "Q" represents the flow rate, "n" is the Manning's roughness coefficient, and "D" denotes the diameter of the pipe. The "k" iteration number is indicated, with Q_{k-1} representing the initial flow rate at the beginning of the loop, and ΔQ_k representing the correction flow rate obtained at the end of the k-th loop.

$$h_L = KQ^n = K\left(Q_{k-1} + \Delta Q_k\right) = K\left(Q^n_{k-1} + nQ^{n-1}_{k-1}\Delta Q_k + n\left(n-1\right)Q^{n-2}_{k-1}\Delta Q_k^2 + \dots\right) \quad (1)$$

It can be expressed as a polynomial expansion.

If the ΔQ_k correction flow rate is small compared to the Q_{k-1} flow rate, the terms containing ΔQ_k with exponents greater than 1 can be neglected.

Additionally, if the ΔQ_k correction flow rate value is considered equal for all pipes in a closed circuit; Equation 2 can be written for an entire closed circuit as:

$$\sum h_L = \sum KQ^n = \sum KQ^n_{k-1} + \Delta Q_k \sum K_n Q^{n-1}_{k-1} = 0 \quad (2)$$

In this case, since the head loss corrections in all pipes will be added arithmetically, if this equation is solved for the correction flow rate ΔQ_k,

$$\Delta Q = \frac{-\sum KQ^n_{k-1}}{\sum KnQ^{n-1}_{k-1}} = \frac{-\sum h_L}{n\sum \frac{h_L}{Q_{k-1}}} \quad (3)$$

The equation is obtained.

For the Darcy-Weisbach relation, since n=2, Equation 4 will take the following form:

$$\Delta Q = \frac{-\sum KQ^2_{k-1}}{\sum 2KQ_{k-1}} = \frac{-\sum h_L}{2\sum \frac{h_L}{Q_{k-1}}} \quad (4)$$

2.3.1.2 Calculation of Balanced Flow Flows

The steady flow rate Q_1 for a pipe with initial flow rate Q_0 and correction flow rate ΔQ is:

$$Q_1 = Q_0 + \Delta Q \quad (5)$$

It is calculated with the equation 5. Similarly, k. If the initial flow rate of the iteration is Q_{k-1} and the correction flow rate is ΔQ_k, the next one is k+1. The balanced flow rate Q_k to be used as the starting flow rate in the iteration:

$$Q_1 = Q_{k-1} + \Delta Q_k \quad (6)$$

It will be calculated with the equation 6.

In the expression obtained in Equation 4, the numerator should be added algebraically, paying attention to the sign, and the denominator should be added arithmetically. The (-) sign in the expression indicates that if there is an excess of load loss in the clockwise direction throughout a closed circuit, DQ_k will be subtracted from the Q_{k-1} iteration initial flow rates in the clockwise direction and will be added to the Q_{k-1} initial flow rates in the counterclockwise direction.

2.4.2. AHP Method

Myers and Alpet originally presented the Analytic Hierarchy Process (AHP) in 1968, and Saaty developed it in 2008 as a practical approach to problem-solving in decision-making. AHP is an MCDM method that allows complex problems to be solved by taking them into account in a hierarchical structure. It can evaluate quantitative and qualitative criteria in decision-making, as well as include the preferences, experiences, intuitions, knowledge, judgments, and thoughts of the group or individual in the decision-making process. When making a decision, the decision-maker may take both subjective and objective factors into consideration. Thus, this circumstance offers the decision-maker the chance to identify their own decision-making processes. (Saaty and Ergu 2015; Awawdeh *et al.* 2024).

The hierarchy in AHP is defined at three levels minimum. Purpose is at the top of the hierarchy. There are primary criteria at a lower level, together with any sub-criteria that may exist. There are options for decisions at the lowest level. Accurate determination of the number of criteria and precise definition of each criterion are necessary for consistent pairwise comparisons. Classifying criteria should be done with consideration for their shared characteristics. AHP can be used with a variety of criteria. It is an excellent process for reaching decisions as a group. Sensitivity analysis makes it feasible to examine the result's elasticity. Experienced and knowledgeable individuals are required because the construction of pairwise comparison matrices and hierarchies is subjective. The algorithmic steps of the AHP method are as follows.

Step 1: The problem is defined. By determining the criteria required for the decision, criteria priorities are determined.

Step 2: A hierarchical structure is created. At the top is the main goal to be achieved. Below that, there are basic criteria and sub-criteria. At the bottom of the hierarchy are the alternatives. The number of stages of the hierarchy depends on the complexity and degree of detail of the problem. When creating a hierarchy, options on the same plane are assumed to be completely independent of each other.

Step 3: Pairwise comparisons matrix is created. Using an importance scale with values between 1 and 9, matrices are created in which decision options are compared according to the criteria, first taking into account the basic criteria, sub-criteria, if any, and finally all criteria. Comparison matrices are a square matrix with diagonal elements of 1.

$$A = a\begin{bmatrix} 1 & a_{12} & \cdots & \cdots & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \ddots & \ddots & a_{2n} \\ a_{31} & a_{32} & 1 & \vdots & \vdots & a_{3n} \\ a_{41} & a_{42} & \vdots & 1 & \vdots & a_{4n} \\ a_{51} & \cdots & \cdots & \cdots & 1 & a_{5n} \\ a_{61} & a_{52} & \vdots & \vdots & \vdots & 1 \end{bmatrix} \quad (7)$$

a, i. is the binary comparison value of criterion and j criterion, and ji a value is obtained from 1 a_{ij}. This property is called the correspondence property. ij a value, “To what extent should the value of criterion i be preferred over another criterion j?” is the answer to the question. Decision options are compared separately according to each criterion. Decision matrices are created using the 1-9 comparison scale suggested by Saaty below (**Table 1**).

Table 1. Comparison Scale (Saaty and Ergu 2015).

Importance	Definition	Explanation
1	Equally important	Both options are of equal importance.
2	Weak or mild	
3	Somewhat important	One criterion was deemed slightly more important than the other.
4	Reasonable plus	
5		One criterion was deemed much more important than the other.
6		
7		The criterion was definitly considered much more important than the other criterion.
8		
9		The criterion was definitly considered much more important than the other criterion.

Step 4: The matrices for pairwise comparisons are normalized. By dividing by the total number of columns in the matrix, each element is normalized. The normalized matrix has a sum of 1 for each column.

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, i, j=1,2, ...,n \quad (8)$$

Equation 8 is used.

Step 5: The vector of priority is computed. By dividing the total of each row in the normalized matrix by the matrix's size, the average is calculated. The importance weights determined for each criterion are represented by these values. The priority vector is made up of these weights.

$$w_i = \left\langle \frac{1}{n} \right\rangle \sum_{i=1}^{n} a'_{ij}, \ i, \ j = 1, 2, \ldots, \ n \quad (9)$$

One uses Equation 9. Consequently, importance values of the criteria in relation to each other are obtained as percentage importance distributions.

Four different paths can be followed in the process of creating the priorities vector. These can be described under the headings The Most General Method, A Better Method, A Good Method, The Best Method. When the comparison matrices are consistent, all four of these methods will give the same result.

Step 6: The ratio of consistency is computed. Following the establishment of priorities and pairwise comparisons, the consistency of the comparison matrices is computed. To ascertain the consistency of a matrix A resulting from a pairwise comparison judgment, one of several methods involves calculating the coefficient known as the "Consistency Index (CI)". The CI coefficient;

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (10)$$

It is calculated with Equation 10. Here,

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\sum_{i=1}^{n} a_{ij} w_i}{w_i}\right) \quad (11)$$

Equation is 11.

$$A \times W = \begin{bmatrix} 1 & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} = 1/a_{12} & 1 & \cdots & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} = 1/a_{1n} & a_{n2} = 1/a_{2n} & \cdots & \cdots & 1 \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad (12)$$

$$d_i = \frac{x_i}{w_i}, i = 1, 2, ..., n \quad (13)$$

$$\lambda_{max} = \frac{\sum_{i=1}^{n} d_i}{n} \quad (14)$$

It is necessary to know the "Random Index (RI)" value in order to assess consistency. **Table 2** provides the RI values defined for n-dimensional comparison matrices.

Table 2. RI values according to the dimensions of the comparison matrices (Saaty and Ergu 2015).

N	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,50	1,50	1,60	1,60

After the CI and RI values are determined, the "Consistency Ratio (CR)" is calculated.

$$CR = \frac{CI}{RI} \tag{15}$$

If the CR defined by Equation 15 is less than 0.10, it is decided that the comparison matrix is consistent.

Step 7: By creating a binary comparison matrix for the criteria, the priority vector of the decision options is calculated. This priority vector can also be defined as the weight vector for the criteria.

Step 8: Decision options are listed. By combining the priority vectors obtained for the criteria, the entire priority matrix is obtained. By multiplying and adding each priority matrix entry with the decision options' priority vector, the result vector is produced. The decision option with the highest weight in this vector is determined as the decision option that should be preferred to solve the problem.

3. Results

3.1. Guidance for Local Governments

First and foremost, the findings of this study, conducted using the Hardy-Cross Method and the GIS-supported AHP Method, provide valuable information for local governments in wastewater infrastructure planning and sustainability decision-making. The Hardy-Cross Method uncovered key inefficiencies in the existing wastewater network, enabling the system to be optimized more effectively. The AHP Method, on the other hand, provided a comprehensive framework for considering multiple factors, such as environmental impact, cost, and social acceptance, in decision-making processes. These findings demonstrate that combining these methods leads to more resilient, cost-effective, and sustainable wastewater management solutions and guides local governments in making informed and holistic infrastructure decisions.

With the steady population growth in Hilvan District, urban expansion has intensified, leading to increased demand for infrastructure and natural resources. Consequently, wastewater treatment and reuse have become critical components of district-level planning, aiming to mitigate water scarcity through the integration of alternative water sources.

In this study, the most suitable location for an alternative wastewater storage facility in Hilvan District, Şanlıurfa Province, was determined through a multi-criteria evaluation process involving six parameters. Utilizing GIS-supported spatial analysis techniques, a series of raster-based thematic maps were generated (**Figure 4**). These maps were further refined through reclassification procedures to standardize and categorize the spatial data layers according to suitability levels.

All spatial datasets, analytical outputs, and georeferenced coordinate information were processed and visualized using ArcGIS 10.5 software. An arithmetic mean approach was applied to the weighted analysis results to evaluate the relative conformity of each pixel to the established environmental and technical standards. Based on the proximity of the data values to threshold criteria, color-coded suitability maps were produced to highlight optimal locations. These outputs are presented in **Figure 4 and Figure 5.**

3.2. Use of ArcGIS Software in Infrastructure Applications

The infrastructure module within ArcGIS software serves as a robust, web-based platform for the planning, management, and implementation of infrastructure projects, including but not limited to drinking water supply systems, wastewater networks, natural gas distribution, and telecommunication lines.

This module facilitates the real-time monitoring and management of infrastructure inventory, enabling users to access detailed records related to line analyses, network interruption diagnostics, and lifecycle assessments of structural components. Through its integrated data management capabilities, the software allows for continuous updating, querying, and visualization of the infrastructure inventory.

Additionally, ArcGIS supports the execution of line analysis and line interruption analysis for various elements within a given infrastructure project. These analytical tools are essential for identifying critical points of failure, optimizing maintenance schedules, and improving overall system reliability. As a result, the infrastructure module significantly enhances the efficiency and accuracy of spatial decision-making processes in urban and regional infrastructure planning.

3.3. Description of Parameters Used in the Study

A 30 m resolution DEM from the NASA SRTM dataset (2000) was used to extract slope and elevation layers. The DEM was reprojected to UTM Zone 37N (WGS84) and filled to remove sinks. For integration with other spatial layers, the raster was resampled to 30 m resolution.

Rainfall: Depending on the source of the water and the degree of purification, wastewater may contain pollutants such as heavy metals, toxic compounds, micropollutants, salts, organic and inorganic substances, and suspended solids. In case of rain, these substances may spread around (Lefta and Hamdan 2024). Therefore, rainfall has both positive and negative aspects on wastewater. For this reason, discharge facilities were designed to discharge rainwater and wastewater together (**Figure 4A**).

Slope: Slope is an important environmental and economic criterion in site selection. Constructing wastewater treatment plants on high slopes will increase excavation and filling costs and will also increase the flow of leachate into surface and underground water resources. In wastewater treatment plant construction, the appropriate slope is 0-2% height and is in the appropriate class. Facilities built in places with a slope of less than 12% prevent surface runoff pollution (Taghilou *et al.* 2019). The slope data layer for Hilvan district was designed at 25x25 resolution using topographic maps.

In case of leakage of waste water, it is easier for this substance to spread around due to the high slope of the ground. Therefore, it may cause the emergence of some diseases in the environment (**Figure 4B**).

Soil Class: soil class that controls sewage infiltration, pollutant sorption and penetration of surface water into landfills, sand and gravel fraction, salinity, alkalinity and solubility affect the permeability of soils. Soils with medium to heavy surface texture, gravel content, salinity and low alkalinity are beneficial for wastewater treatment plant construction (Topuz and Deniz 2023).

Untreated wastewater used for irrigation may increase the risk of waterborne diseases. When the pathogens and their effects on human health are examined, the infections that occur due to treated and untreated wastewater are typhoid fever, cholera, giardiasis (diarrhea), dysentery, and infectious hepatitis diseases (**Figure 4C**).

Land Use: It is among the most important factors regulating surface flow due to evaporation and transpiration; it all depends on factors such as vegetation type and soil wetness. As a result, it has a significant impact on both surface water and groundwater recharge (Ifediegwu 2022) (**Figure 4D**).

Land use data were obtained from the 2018 CORINE Land Cover dataset (100 m resolution) and reclassified into six categories relevant to wastewater treatment site suitability. The layer was projected to UTM Zone 37N (WGS84), rasterized, and normalized to assign suitability weights for the GIS–AHP analysis

Generally, land use is controlled by land vegetation, which is used for various purposes such as agriculture, industry and housing. Land use aims to protect "sensitive" areas under economic development (Abdalla and El Khidir 2017). It is important for areas such as residential areas, agricultural areas, vineyards and gardens. The land use map was designed with GIS software program. Pastures and groves are suitable environments for the construction of wastewater treatment plants.

Geology: It is an earth science that determines the penetration and percolation of water. It is a very important criterion to evaluate the potential of water. The high permeability and porosity of geological units increases groundwater storage and productivity (Yildirim 2021). Therefore, in the event of a wastewater explosion or cracked pipes, water leakage may cause contamination of both groundwater and surface water (**Figure 4E**).

Geological maps were obtained from the 1:250,000 scale maps provided by the MTA (2020) and reprojected to UTM Zone 37N. Geological units were rasterized at 30 m resolution and normalized to reflect their suitability for wastewater treatment infrastructure.

Geomorphology: Geomorphology Maps are maps that provide information about the shaping process in a region, that is, the landforms formed under the influence of internal and external forces (Awad and Shleha 2020). Faults, valley types, debris cones, terraces, plains and many other landforms on a map are scanned and shown. These maps are colored in order to easily distinguish landforms (**Figure 4F**).

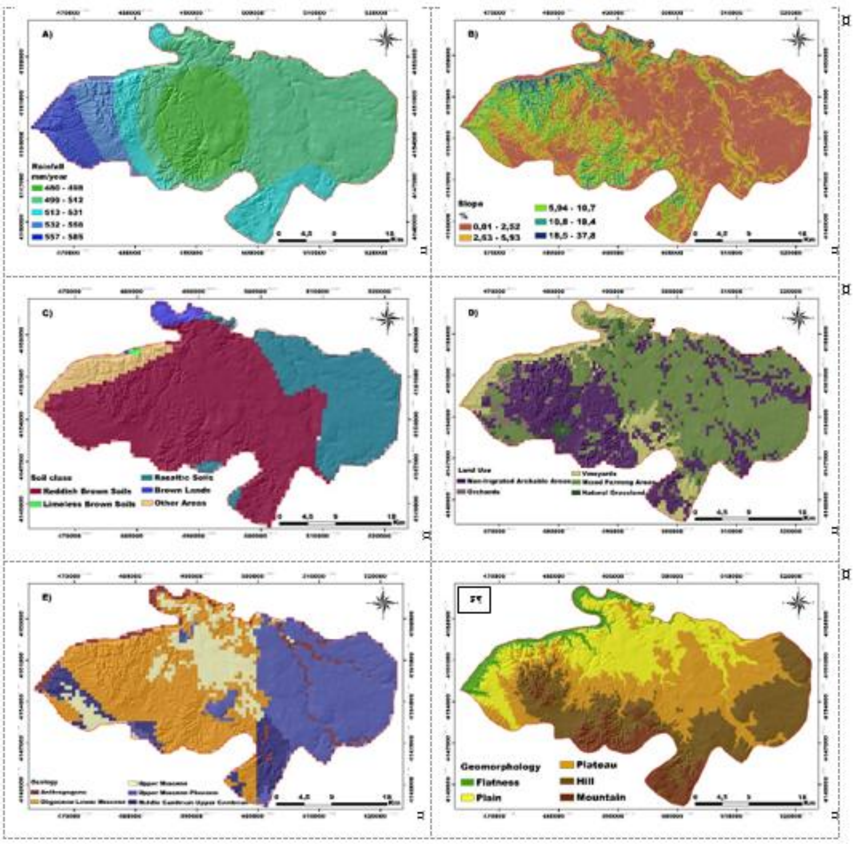


Figure 4. Thematic Raster Maps Created in ArcGis, ArcMap 10.5 Environment (**(a)** Rainfall, **b)** Slope, **c)** Soil Class, **d)** Land Use, **e)** Geology, **f)** Geomorphology)

In the light of these explanations, 6 parameters (precipitation, slope, soil class, land use, geology, geomorphology) considered for use in the AHP environment were evaluated in the ArcGIS environment and raster maps were produced (**Figure 4**).

In the MCDM system, it is important to standardize data to create compatibility and integrity produced by various units and dimensions with ordinal, interval, nominal and ratio scales (Al Nasiri *et al.* 2023). Although various approaches exist for standardizing criterion maps, the most commonly used method is linear scale transformation. After the raster thematic maps were produced, these 6 parameters were reclassified (**Figure 3**).

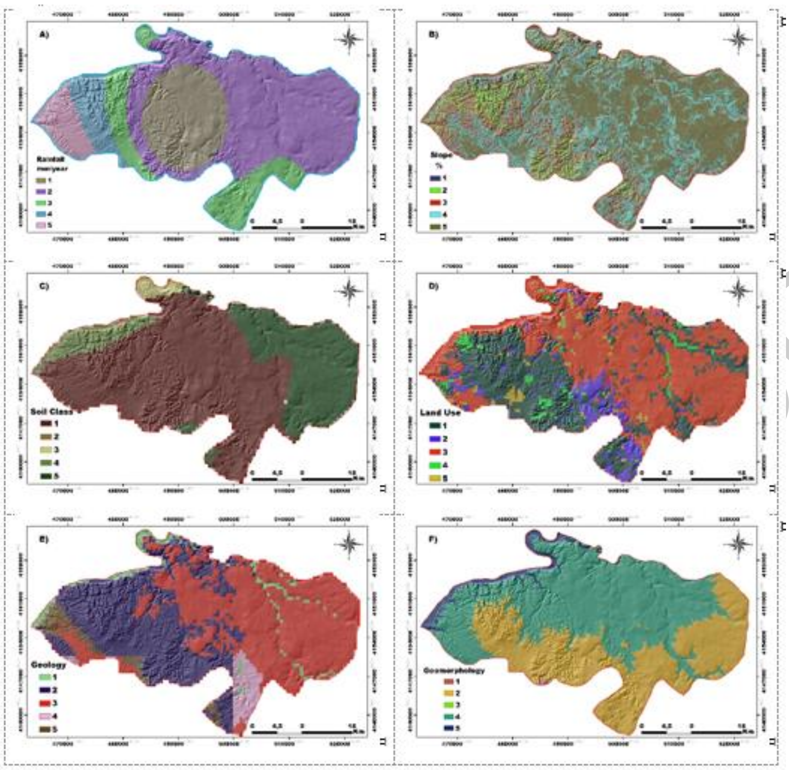


Figure 5. Reclassification of Raster Maps Created in ArcMap Environment (**(a)** Rainfall, **b)** Slope, **c)** Soil Class, **d)** Land Use, **e)** Geology, **f)** Geomorphology)

The integration steps and data flow between GIS and AHP method are given schematically in **Figure 6**.

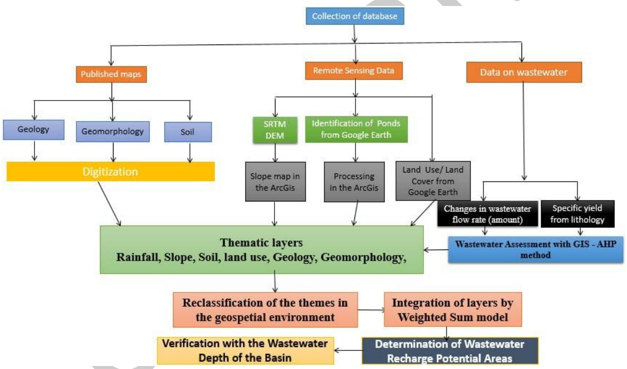


Figure 6. Schematic flow of the study area using GIS and AHP methods.

After the classification of the parameters, the AHP method was applied.

3.4. AHP Method Application

The weights of the parameters were determined using the AHP method, which enables the explicit listing of both concrete and abstract criteria in the process of prioritization. This process involves decomposing a problem from the primary goal into secondary-level criteria and alternatives. A pairwise comparison matrix of every element at every level is produced after the hierarchy is constructed. The AHP method facilitates group decision-making by allowing members to apply their knowledge, values, and experiences to break down a problem into a hierarchy and solve it using the AHP steps. The tables below show how the AHP method was applied in this study in each respective case.

Table 3. Pairwise comparison matrix of 6 parameters.

Criteria	Assigned Weight	Rainfall	Slope	Soil Class	Land Use	Geology	Geomorphology
Rainfall	9	1,000	0,889	0,778	0,667	0,556	0,444
Slope	8	1,125	1,000	0,875	0,750	0,625	0,500
Soil Class	7	1,286	1,142	1,000	0,857	0,714	0,571
Land Use	6	1,500	1,333	1,167	1,000	0,833	0,667
Geology	5	1,800	1,600	1,400	1,200	1,000	0,800
Geomorphology	4	2.250	2,000	1,750	1,500	1,250	1,000
Total		8,961	7,964	6,970	4,489	4,978	8,482

In this study, six primary parameters used in the site selection analysis for the wastewater treatment system were weighted according to their relative influence on the system's performance. The weighting process was conducted using the Analytic Hierarchy Process (AHP) method, considering each parameter's impact on treatment efficiency, environmental sustainability, and technical feasibility. The resulting parameter weights are presented in **Table 3**.

Following the initial weighting, a pairwise comparison matrix was developed, and the consistency ratio (CR) was calculated to assess the reliability of the decision model. The final weight values, derived from the normalized comparison matrix, were then used in the spatial decision-making process. Detailed calculations and final weights are provided in **Table 4**.

Table 4. Normalization and geometric mean after pairwise comparison matrix.

Criteria	Rainfall	Slope	Soil Class	Land Use	Geology	Geomorphology	Geometric Mean	Normalized Weight
Rainfall	0,1116	0,1116	0,1116	0,1486	0,1117	0,0523	0,1079	0,7574
Slope	0,1255	0,1256	0,1255	0,1671	0,1256	0,0589	0,1214	0,7882
Soil Class	0,1435	0,1434	0,1435	0,1909	0,1434	0,0673	0,1387	0,8520
Land Use	0,1674	0,1674	0,1674	0,2228	0,1673	0,0786	0,1618	0,9709
Geology	0,2009	0,2009	0,2009	0,2673	0,2009	0,0943	0,1942	1,3652
Geomorphology	0,2511	0,1116	0,2511	0,3342	0,2511	0,1179	0,2195	1,4170

Table 5. Criteria and Subcriteria Ranges Used in Wastewater Treatment Evaluation.

Flood Causative Criterion	Unit	Class	Ratings and Susceptibility Class Rangers	Ratings for Susceptibility Classes	Weight (%)
Rainfall	mm/year	510 – 535	Very Good	8	24
		536 – 562	Good	7	
		563 – 590	Reasonable	6	
		591 – 626	Risky	3	
		627 – 682	Very Risky	2	
Slope	%	0.10 - 2.74	Very Good	7	20
		2.75 - 5.89	Good	6	
		5.90 - 9.72	Reasonable	5	
		9.73 - 15.1	Risky	4	
		15.2 - 34.9	Very Risky	3	
Soil Class	Level	Reddish Brown Soils	Very Good	8	17
		Brown Soils	Good	7	
		Other Areas	Reasonable	5	
		Alluvial Soils	Poor	4	
		Reddish Brown Soils	Very Poor	3	
Land Use	Level	Agricultural Areas	Very Good	7	15
		Mixed Farmlands	Good	6	
		Continuously Irrigated Areas	Reasonable	5	
		Orchards	Poor	3	
		Olive Groves	Very Poor	2	
Geology	Level	Eocene	Very Poor	2	13
		Quaternary	Poor	3	
		Miocene	Reasonable	4	
		Pliocene - Quaternary	Good	5	
		Upper Miocene	Very Good	6	
Geomorphology	Level	Flatness	Very Good	6	11
		Plain	Good	5	
		Plateau	Reasonable	4	
		Hill	Risky	3	
		Mountain	Very Risky	2	

$$\text{Average } \lambda_{max} = \frac{\sum \frac{\text{Normalized Weight}}{\text{Geometrik Mean}}}{6} = 6{,}15072$$

$$\text{CI} = \frac{\lambda_{max} - n}{n-1} = \frac{6{,}15072 - 6}{6-1} = 0.030144$$

$$\text{CR} = \frac{\text{CI}}{\text{RI}} = \frac{0.030144}{1{,}24} = 0{,}0243097$$

Since the calculated Consistency Ratio (CR) value is below the threshold of 0.1, as proposed by Saaty (1980), the results indicate an acceptable level of consistency in the pairwise comparison matrix. Therefore, the application of the AHP in this study is deemed methodologically valid and reliable.

By integrating the spatial data of six different raster maps produced previously with the criteria weights obtained with the Analytical Hierarchy Process (AHP) method, **Table 5** was created, which includes the criteria taken into consideration in the wastewater treatment plant location selection and the sub-criteria ranges of these criteria.

Based on the criteria and sub-criteria ranges defined in **Table 5**, the Geographic Information Systems (GIS) analysis process was initiated, and the final suitability map for wastewater treatment plant site selection was generated using ArcMap software.

3.5. Wastewater Treatment System Result Map

In this study, a MCDM approach was applied to identify the most suitable alternative location for a wastewater storage and treatment facility within the Hilvan district of Şanlıurfa province. The decision-making process was carried out by integrating the AHP method with GIS based spatial analysis techniques. Six main parameters; slope, distance to residential areas, agricultural land use, proximity to water resources, geological structure, and distance to transportation networks were taken into account to conduct a suitability analysis, and the final result map was produced in raster data format using ArcMap software.

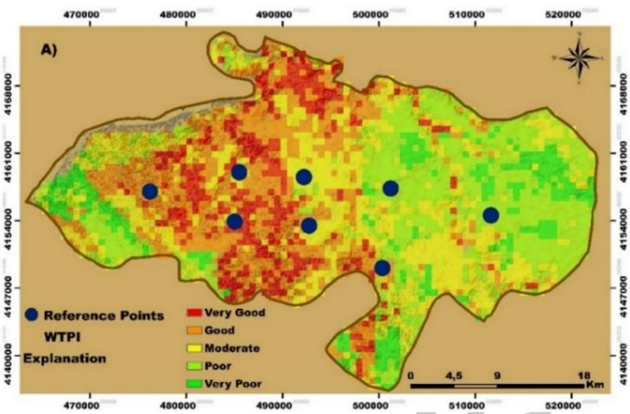


Figure 7. Wastewater Treatment Potential Index (WTPI) Map

Based on the analysis, the study area was classified into five suitability categories: unsuitable, less suitable, moderately suitable, suitable, and highly suitable. In addition, due to legal and regulatory restrictions, 52% of the study area was designated as prohibited for development and excluded from the analysis. For the remaining area, the distribution of suitability classes is as follows: 19.89% unsuitable, 18.75% less suitable, 30.80% moderately suitable, 20.80% suitable, and 10% highly suitable (**Table 6**).

Table 6. Classification according to Hilvan District Wastewater Treatment values.

Flood Risk Value	Definition	Rate (%)	Total area (1296 km²)
172 – 228	Very Goodr	10.00	129,60
229 – 255	Good	20.80	269,57
256 – 281	Moderate	30.56	396,06
282 – 307	Poor	18.75	243,00
308 – 358	Very Poo	19.89	259,06

As a result of comprehensive spatial and environmental evaluations, specific zones within the Hilvan district boundaries were identified as the most appropriate areas for the establishment of a wastewater treatment facility. These areas were found to be optimal in terms of both land use compatibility and environmental considerations. Furthermore, a key objective of the proposed site selection is to reduce the cost of transporting wastewater by minimizing the distance between wastewater generation points and treatment locations, thereby contributing to a more sustainable and cost-effective environmental management strategy.

The final suitability map generated in this study serves as a valuable decision-support tool for planners and policymakers in the development of wastewater infrastructure in the region.

3.6. Hardy-Cross Method and Its Application

As seen below, the flow rate passing through each pipe in the network consisting of two loops (these eyes and the pipes on them are named) was determined using the Hardy-Cross method. K values are given in the figure. The numbering of six pipes around the network is shown in the figure.

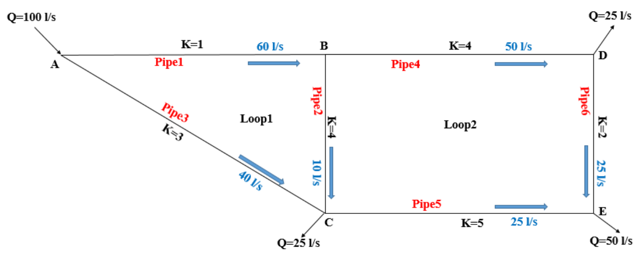


Figure 8. Two-Eye Network

1. The geometry of the network was examined, and the flow rates of the pipes were estimated in accordance with the principle of continuity, taking into account the flow rates entering and leaving the network, in reasonable directions and levels.
2. The 100 l/s flow rate entering the system from point A in the network is divided into 60 l/s and 40 l/s flow rates through AB and AC branches, respectively. At point C, the inlet flow rate of 50 l/s in total, 40 l/s from the AB pipe and 10 l/s from the BC pipe, the 25 l/s drawn flow rate and the 25 l/s flow rate flowing through the CE pipe is 50 l. /s is equal to the output flow rate.

3. At the beginning, the flow rate, flow direction and K number of each pipe forming the network are certain. For each eye (loop), DQ correction flow rates are obtained by calculating the K_0^n and K_n K_0^(n-1) values of the pipes and their sums. In the system that will be solved with the Darcy-Weisbach relation, the n value in the relations will be taken. According to this,

I. For the Eye :

AB (1) Pipe	$KQ_0^2 = +1\times 60^2 = 3600$	$2KQ_0 = 1\times 2\times 60 = 120$
BC (2) Pipe	$KQ_0^2 = +4\times 60^2 = 400$	$2KQ_0 = 4\times 2\times 10 = 80$
AC (3) Pipe	$KQ_0^2 = -3\times 40^2 = -4800$	$2KQ_0 = 3\times 2\times 40 = 240$
I. Eye Totals	$\sum KQ_0^2 = -800$	$\sum 2KQ_0 = 400$

$\Delta Q_1 = -800/440 = -1.821/s$

II. For the Eye :

BD (4) Pipe	$KQ_0^2 = +4\times 50^2 = +1000$	$2KQ_0 = 4\times 2\times 50 = 400$
AB (1) Pipe	$KQ_0^2 = +2\times 25^2 = +5050$	$2KQ_0 = 2\times 2\times 25 = 100$
AB (1) Pipe	$KQ_0^2 = -4\times 10^2 = -400$	$2KQ_0 = 2\times 2\times 10 = 400$
AB (1) Pipe	$KQ_0^2 = -4\times 10^2 = -400$	$2KQ_0 = 4\times 2\times 10 = 800$
II. Eye Totals	$\sum KQ_0^2 = +7725$	$\sum 2KQ_0 = 830$

$\Delta Q_2 = 7725/830 = 9.31\ 1/s$

4. The correction flow rates found are added to the initial flow rates. The point to be considered here is the signs of the correction flow rates. The negative sign of the DQ1 term means that the correction flow rate is added to pipes with positive flow direction, that is, the flow direction is clockwise, and subtracted from pipes with negative flow direction. If the DQ1 value is positive, which is the opposite of this situation, the correction flow rate is subtracted from the pipes with positive flow direction and added to the pipes with negative flow direction. The corrected flow rates obtained in this way are shown in **Figure A.**
5. The next iteration is carried out with the corrected flow rates obtained in the 4th article, that is, step 3 and step 4 are repeated with the corrected flow rates. In this way, iterations are continued until the DQI drops below a specified value.

4. Conclusion and Recommendations

Wastewater pollution in rivers and streams continues to pose a major environmental challenge, underscoring the need for effective treatment technologies prior to discharge into natural ecosystems. The primary purpose of wastewater treatment is to manage domestic, agricultural, and industrial effluents without endangering public health or ecological integrity. Although the reuse of treated wastewater in irrigation can be beneficial, its sustainable application depends on proper operational control, continuous monitoring, and compliance with quality standards.

This study proposed an integrated decision-support framework that combines the GIS-based Analytic Hierarchy Process (AHP) with the Hardy–Cross hydraulic balancing method to optimize wastewater treatment planning in the Hilvan District of Şanlıurfa, Türkiye. In contrast to conventional approaches that evaluate spatial suitability and hydraulic performance separately, the presented model simultaneously incorporates spatial, environmental, and hydraulic constraints. Multi-criteria layers—including slope, land use, precipitation, soil type, geological structure, and geomorphology—were weighted using the AHP method and integrated into GIS to identify optimal plant locations. In parallel, Excel-based Hardy–Cross iterations were applied to assess flow distribution, energy losses, and pressure balance along the sewer network.

Water Quality Index (WQI) analysis and IDW interpolation identified five spatial clusters, with sampling points in the southern and southwestern regions (e.g., SL7 and SL8) showing "poor" to "very poor" water quality. These results highlight the influence of unregulated industrial discharges, inadequate riparian protection, and uncontrolled urban runoff. The findings emphasize the need for stronger regulatory enforcement, improved monitoring infrastructure, and early-warning systems.

Sensitivity analysis confirmed the methodological reliability of the model, revealing slope (35%) and land use (25%) as the most influential criteria, while soil type had a limited effect (3%). Variations of ±10% in criteria weights produced minimal changes in suitability zones (±4.5–6.2%), and DEM resampling had negligible impact on the final outputs.

5. Limitations of the Study

Although the integrated GIS-AHP and Hardy–Cross approach proved effective, several limitations should be acknowledged to guide future research:

5.1. Data Resolution and Availability

Some datasets (e.g., DEM, soil maps, land use) were limited to 30-m spatial resolution, which may affect the precision of micro-scale site suitability analyses. Access to higher-resolution satellite imagery or LiDAR could improve accuracy.

5.2. Institutional Data Constraints:

A significant portion of hydraulic, demographic, and infrastructural data was obtained from public institutions. These datasets may contain inconsistencies, temporal gaps, or generalized values that could introduce uncertainty.

5.3. Hydraulic Model Simplification:

The Hardy–Cross method, while transparent and practical, is an iterative approximation. More advanced hydraulic solvers (e.g., EPANET, SWMM) could provide more detailed simulations, especially for transient conditions.

5.4. Limited Field Verification:

Due to institutional and logistical constraints, extensive field validation of soil structure, groundwater depth, and pipeline behavior could not be performed. Ground truthing would enhance model reliability.

5.5. Temporal Variability Not Modeled:

Climate variability, extreme precipitation, and seasonal wastewater fluctuations were not dynamically incorporated. Future studies should integrate time-series analysis or hydrological modeling to capture these variations.

6. Recommendations

- To strengthen sustainable wastewater management and enhance system performance, the following actions are recommended:
- Integrating continuous field measurements and expert-validated datasets into GIS and hydraulic models;
- Developing real-time monitoring systems using IoT-enabled sensors for influent, process, and effluent tracking;
- Expanding the model with advanced hydraulic simulation tools for transient and peak-flow conditions;
- Enhancing local policy frameworks to ensure regulatory compliance, risk reduction, and public awareness;
- Investing in professional training and scientific capacity building for municipal water infrastructure management.

The proposed study provides a solid foundation for both future research and real-time implementation because it integrates two scalable components: GIS-based spatial optimization and Hardy–Cross hydraulic modeling. The methodology can easily be updated with new spatial datasets, population projections, climate variables, or sensor-based flow measurements, making it suitable for future academic studies, model refinement, and cross-regional comparisons.

For real-time implementation, the framework offers practical advantages for municipalities: it identifies optimal plant locations, reduces hydraulic energy losses, and supports cost-effective infrastructure planning. Since all analyses are based on widely used tools (GIS, AHP, and Excel-based hydraulic modeling), the approach can be directly adopted, expanded with IoT monitoring systems, or integrated into existing water management workflows.

Comparative evaluation shows that the proposed integrated framework achieves a higher spatial suitability score (38.6%) compared with similar GIS-based MCDA studies (32%–36%). Additionally, Hardy-Cross-based hydraulic balancing reduced total head losses by 12%, a feature absent in previous site-selection-only studies. These improvements demonstrate both spatial and hydraulic performance advantages of the proposed system.

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