Water Supply

© 2023 The Authors Water Supply Vol 23 No 9, 3805 doi: 10.2166/ws.2023.222

Site suitability analysis of water tank in Athivilai village of India using an analytical hierarchy process and a geographical information system

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ABSTRACT

In uneven terrain regions, the water tank location plays a significant role in pressure distribution and economical pipe sizes in the water distribution system. This study aimed to determine suitable tank locations by the analytical hierarchy process (AHP) and geographical information system (GIS). Factors such as elevation, slope, population, land use land cover, and distance to the road are considered for this analysis. Thematic maps are created in ArcGIS and weights are determined using the AHP method. From the weighted overlay analysis, the result shows that 15.59, 52.36, 31.31, and 0.63% of the areas are suitable, moderately suitable, least suitable, and unsuitable, respectively. Since the area has an elevation range of 27–87 m, it is divided into three zones. An unsuitable location falls only under one zone; therefore, the results are tested in EPANET by locating the tanks in suitable and least suitable locations. Locating the tanks in suitable locations reduces the size of pipes economically and maintains the pressure successfully while locating the tanks in the least suitable locations creates a negative pressure and increases the pipe size. This study helps the designers to obtain an effective design of a water distribution network by evaluating suitable tank locations.

Key words: analytical hierarchy process, effective design, EPANET, geographical information system, water tank location, weighted overlay analysis

HIGHLIGHTS

- Water tank location plays an effective role in reducing the size of pipes.
- Effective design of the WDN can be achieved by locating water tanks in suitable locations.
- Integration of AHP and GIS to determine the suitable location of a water tank.

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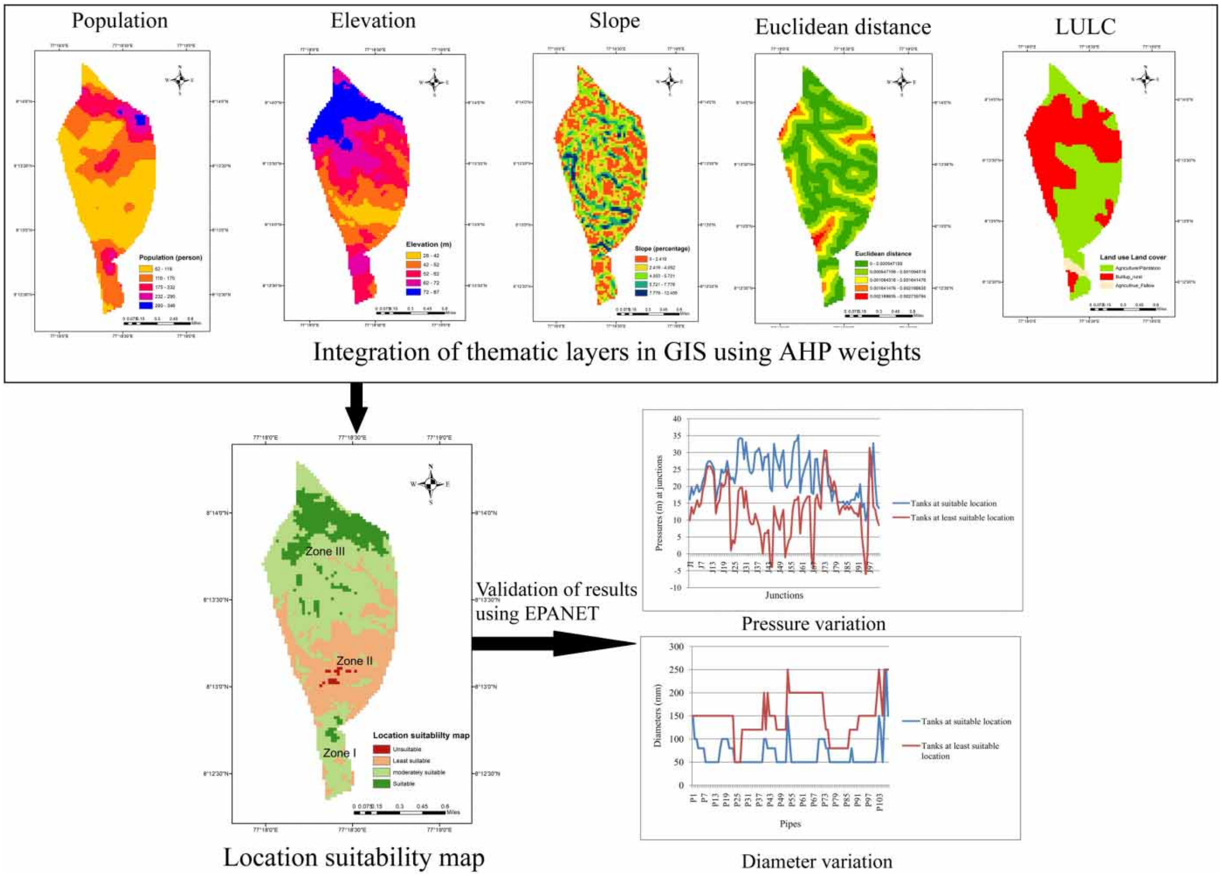
GRAPHICAL ABSTRACT



INTRODUCTION

The water distribution system (WDS) serves as an infrastructure to supply water to consumers. In India, there is a need for the construction of new water distribution networks (WDNs) in various regions. The design must be such that water is available to consumers throughout their design period with adequate pressure. The adequate supply of water received by the consumers depends on the pressure maintained in the system. This can be fulfilled by the storage tank because it helps to maintain the desired pressure in the mains constantly, even in remote areas (Birdie & Birdie 2010; Garg & Garg 2010; Briere 2014). In the absence of water tanks, the pressure falls as the demand increases. This is because the water tank provides the head that drives the WDN (Mercy & Tiku 2018). Also, the storage tank enables demand management, assures water supply in case of network failure and reserves for emergencies such as firefighting, and allows the modulation of pump flow rate.

The WDN costs about 40–70% of the total cost of the water supply project (CPHEEO – Central Public Health and Environmental Engineering Organisation 1999). Thus, an optimized design is important while designing a new network. The majority of the studies focused on the optimization of the WDN that considered diameter as the main optimization problem because reducing the size of pipes reduces the overall cost of the water supply project (Vasan & Simonovic 2010; Kang & Lansey 2012). Providing a water tank also results in the overall reduction of the size of pumps, pipes, and treatment units (Birdie & Birdie 2010). However, an inadequate design of the WDN or improper location of the water tank increases the cost of pipe and pump operation and reduces the network performance indices such as resilience and reliability (Vamvakeridou-Lyroudia *et al.* 2007). However, when these tanks are properly designed and located, they are a cost-effective means of improving the overall performance of the network. Gottipati & Nanduri (2014) developed an index called the uniformity coefficient to measure the unity in the distribution of the intermittent WDN and their results indicated that the layout and the location of the tank play a significant role in improving equity in distribution within the network. Thus, the location of the storage tanks plays an important role in the effective design and overall performance of the network.

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The research works considering water tank location in optimization are as follows: Ameyaw *et al.* (2013) developed a multi-objective optimization method GANetXL to improve the equitable distribution of water in intermittent systems. They concluded that equity can be improved by the optimal location and capacity of elevated water tanks. Hooda & Damani (2017) developed an Integer Linear Program (ILP) model in which they considered tank configuration as a variable for optimization. The implementation was done by using Java 7 and GLPK 4.55 Linear Program Solver which uses Google Map's API (Application Programming Interface) for GIS functioning. Abarca & Da Silva (2020) proposed a methodology to locate the water tanks in rural Andean areas by developing a protocol based on the interaction between water supply hydraulics and GIS. The algorithm is based on parameters such as pressure limit, gravity supply, accessibility, stability, and proximity of the largest population density. Basile *et al.* (2008) developed a two-stage algorithm to optimize the water storage location and capacity. They linked the model with the hydraulic solver EPANET. They applied the algorithm to the existing network and spotted two possible locations for introducing tanks and an analysis was done to find the best among them. From the above literature, it can be noted that the inclusion of water tank location plays a significant role in the optimization of the WDN.

The current development in the Geographic Information System (GIS) serves as a powerful tool for the collection, storage, and management of spatial data in a simplified matter (Goitsemang *et al.* 2020). GIS plays an important role in viewing the results through spatial and visual interpretations (Saranya & Saravanan 2020). Application of AHP integrated with GIS has developed a lot since the beginning of the 21st century (Marinoni 2004; Mardani *et al.* 2015). Several studies have been done by integrating GIS and AHP techniques to find the vulnerability characteristics and the spatial distribution of water resources in Guiyang city (Li *et al.* 2022), to evaluate the dam site for Bortala, in Northwest China (Dai 2016), to delineate the groundwater potential zones (Saranya & Saravanan 2020; Mahato *et al.* 2022; Sarkar *et al.* 2022), evaluate suitable site selection for solar farms (Uyan 2013), develop a dam site suitability model for lower Tapi basin (Raaj *et al.* 2022), and to generate a Seismic Vulnerability Index for Water Distribution Networks (SVI-WDNs) (Marleni *et al.* 2022).

Although there have been many studies to design the WDN coupled with GIS and AHP, there is no research on site selection for the location of water tanks. Moreover, in previous research studies, authors have developed a protocol or an algorithm linked with GIS to find the tank location. This study aims to find the weights of the factors that influence the tank location using AHP. Then, weighted overlay analysis is used to find the location in the ArcGIS environment. The results are tested by using EPANET by locating the tanks in suitable and least suitable locations.

MATERIALS AND METHODS

Study area and data

Athivilai village of Kanyakumari district, Tamilnadu, India is chosen for this study. As per census 2011, the village has a land area of 4.05 km^2 and a population of 7,401. The boundary of the study area is digitized from the survey of India toposheet C43X/8. The geographical extent of the study area varies from 8°12′20.56″N to 8°14′18.33″N and 77°17′58.46″E to 77°18′44.55″E (Figure 1).

The normal rainfall of the district is about 1,304 mm. The depth of groundwater level in hard rock areas ranges from 0.4 to 11.2 m. The elevation of the study area varies from 28 to 87 m with respect to the mean sea level. Various factors that influence the location of water tanks are selected based on experience and the availability of data from the study area. Factors such as elevation, slope, land use and land cover (LULC), population, and distance to the road are considered for the present study. Thematic layers were created in ArcGIS. The slope and elevation map were extracted from the Shuttle Radar Topography Mission (SRTM) DEM 30 m resolution data. As per census 2011, the population of the area is 7,401. Considering a growth rate of 1.32% as per Jal Jeevan guidelines, the future estimated population for the year 2051 was found to be 12,505. At the junction points of the WDN, population data were found, and thereby, a population map was created using the inverse distance weighted (IDW) tool in ArcGIS. The LULC map was developed from Landsat 8 OLI using the supervised classification tool in ArcGIS. The road map was digitized using Google Earth Pro image. The proposed methodology is shown in Figure 2.

Determination of weights by AHP method

Various factors such as demand, population, land use land cover, slope, and distance to the road influence the location of water tanks. Multi-criteria decision-making (MCDM) is a method to evaluate the appropriate weights which influence each other. The Analytical Hierarchy Process (AHP) is one of the MCDM methods, which is simple and most commonly

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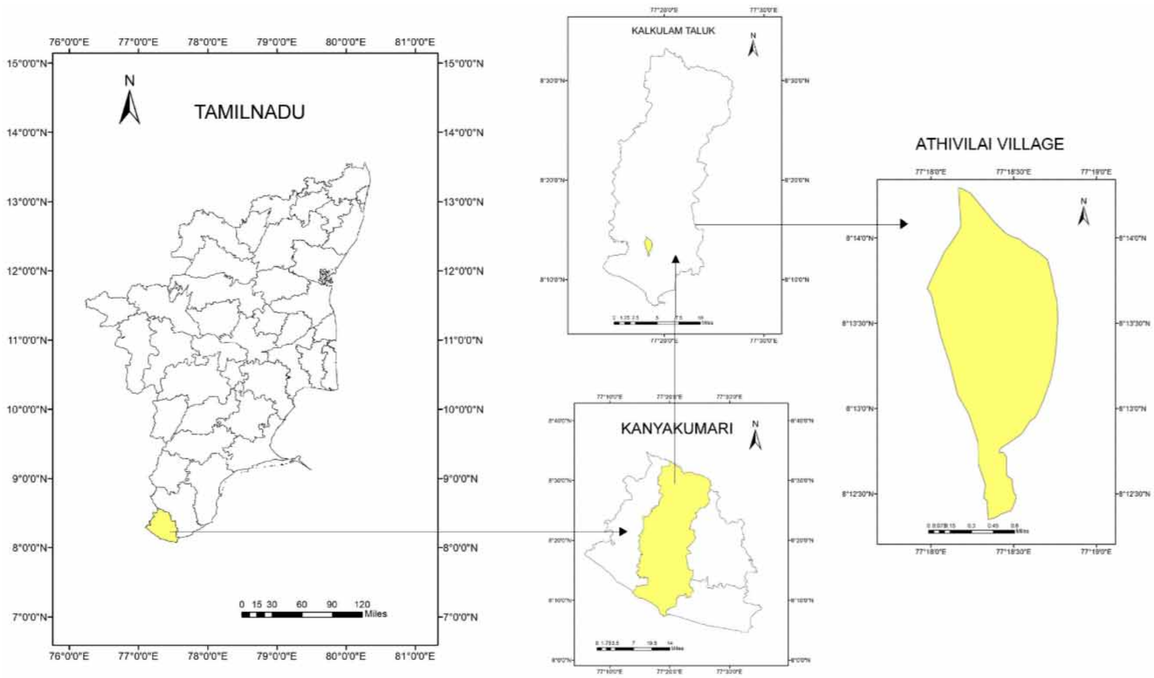

Figure 1 | Study area location.

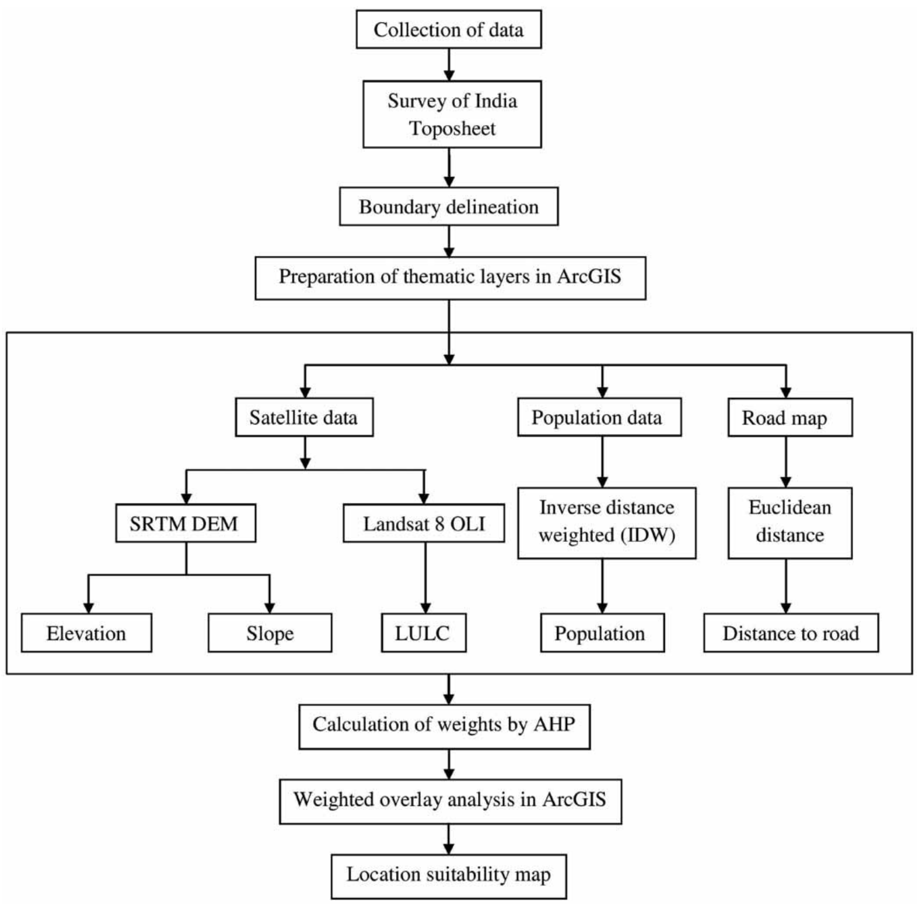

Figure 2 | Methodology.

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used, that helps in making decisions in complex situations and in the field of sustainable engineering (Stojcic *et al.* 2019). The AHP consists of three levels which include the identification of decision goals, criteria, or factors, the evaluation of pairwise comparisons between each element at every level of the hierarchy, and synthesis using the solution algorithm from the results of pairwise comparisons over all the levels (Wind & Saaty 1980; Saaty 1988, 1990). The AHP method is a process that uses an expert's opinion to determine the weights and ranks of factors by constructing a pairwise comparison matrix based on Satty's scale of importance (Table 1).

All factors influencing the water tank location are compared with each other in pairs and the comparison matrix is created, as given in Table 2.

The normalized matrix was created by dividing each element by the sum of all elements in their respective column. The average of the row elements of the normalized matrix gives the weights of factors (Saaty 1977, 1988). Some degree of inconsistency may arise because the comparisons are based on an expert's opinion; therefore, a consistency check has to be performed. The constructed matrix is said to be consistent if the consistency ratio (the ratio of consistency index (CI) to random index (RI)) is less than 10% (Saaty 1977). RI depends on the number of factors. Since five factors are considered in this study, RI is 1.12 (Table 3). The CI was determined using Equation (1):

$$\text{Consistency index} = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

where $\lambda_{\max}$ represents the largest Eigen value of the pairwise comparison matrix and n represents the number of factors considered.

The consistency ratio was calculated using Equation (2):

$$\text{Consistency Ratio (CR)} = \frac{\text{CI}}{\text{RI}} \tag{2}$$

From Table 4, it can be noted that the CR is 0.0639 which is less than 0.1; thus, the comparison matrix is said to be consistent.

Table 1 | Satty's fundamental scale (Saaty 1970)

Intensity of importance	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between two judgements

Table 2 | Pairwise comparison matrix

Factors	Elevation	Population	Slope	Distance to road	LULC
Elevation	1	2	3	2	3
Population	1/2	1	2	3	3
Slope	1/3	1/2	1	3	2
Distance to road	1/2	1/3	1/3	1	2
LULC	1/3	1/3	1/2	1/2	1
SUM	2.67	4.17	6.83	9.50	11.00

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Table 3 | Random index (R.I.)

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 4 | Normalized matrix with weights of the factors

Factors	Elevation	Population	Slope	Distance to road	LULC	Weights	
Elevation	0.38	0.48	0.44	0.21	0.27	0.3555	$\lambda_{max} = 5.28$
Population	0.19	0.24	0.29	0.32	0.27	0.2617	CI = 0.0716
Slope	0.13	0.12	0.15	0.32	0.18	0.1778	RI = 1.12
Distance-to-road	0.19	0.08	0.05	0.11	0.18	0.1207	CR = 0.0639
LULC	0.13	0.08	0.07	0.05	0.09	0.0843	

Weighted overlay analysis

The thematic maps created are reclassified and the ratings are assigned as per their importance with each other. In weighted overlay analysis, these maps are converted into a common scale of measurement, and then, the weights obtained through AHP were assigned to each factor. Thus, a location suitability map was created by multiplying the weights of each factor with their ranks as shown in Equation (3):

$$\text{Location suitability map} = E_w \times E_r + S_w \times S_r + P_w \times P_r + D_w \times D_r + \text{Lu}_w \times \text{Lu}_r \quad (3)$$

where E_w, S_w, P_w, D_w, and Lu_w represent the weights of elevation, slope, population, distance to the road, and land use land cover, respectively, and E_r, S_r, P_r, D_r, and Lu_r represent the ranks of elevation, slope, population, distance to the road, and land use land cover, respectively.

Analysis in EPANET

After finding location suitability mapping of the ungauged study area, validation is carried out in EPANET. An analysis is done by locating tanks in (1) suitable locations and (2) least suitable locations. EPANET is a computer software used to simulate the hydraulic and water quality behavior of pipe networks. The rate of flow and velocity of water in pipes, the pressure at junctions, the height of water in storage tanks, and the concentration of chemical species can be found throughout the network. EPANET models a WDN as a collection of pipes connected to junctions (Rossman 2000). With the help of EPANET, the effective design of a WDN can be done within a short period, even for the complex type of networks (Ramana *et al.* 2015). EPANET analysis is less time-consuming when compared to Excel programming. Moreover, graphs of demand, nodal pressure, and diameter of links can be obtained without any tedious work (Rai & Lingayat 2019).

For EPANET analysis, the following steps are involved: The junctions are fixed along the road network and the latitudes and longitudes are found at the junctions using GPS surveying. The input data required for the junctions are base demand and elevation. Likewise, the inputs required for pipes are length and roughness coefficient. The demand at the junctions is obtained by multiplying the population at junctions with the rate of supply. The rate of supply is taken as 80 lpcd (liter per capita per day) as per CPHEEO (1999). The elevation and the pipe length can be obtained from Google Earth Pro (Sathyanathan *et al.* 2016). Furthermore, the area is divided into three zones since the elevation ranges from 27 to 87 m. This is because when the elevation difference varies between 15 and 25 m (CPHEEO 1999), this region has to be divided into three zones. Also, if an individual tank is provided for the whole zone, then the whole system is shut down for repair when the pipe at any point of the network fails, which makes the consumers suffer. Each zone is assumed to have individual tanks. The input data for the junctions, pipes, and tanks are assigned. The diameters are randomly fixed by trial and error method in such a way that the pressures are within the limits, i.e. the diameters are fixed such that the water is available at the endpoints of the junctions with the allowable pressure even at the time of maximum demand (Garg & Garg 2010).

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In this study, initially, all diameters are assumed to be 100 mm for EPANET analysis and adjusted to get the optimum diameter with respect to the required pressure at the junctions (Ramana & Sudheer Chekka 2018).

RESULTS

The weights obtained through AHP are assigned over the factors and the location suitability map was created. It is divided into five different classes, 1–5, corresponding to unsuitable, least suitable, moderately suitable, suitable, and highly suitable, respectively.

Population

Water demand is the product of population and per capita demand. Water demand is directly related to the population. Thus, as the population of the area increases, the water demand also increases. The demand for the highly populated area is more than that of the less populated area.

Water tanks are to be placed near high-demand areas (Mays 2000). Therefore, they must be located near a highly populated area so that adequate pressure can be supplied. Here, to create the population map, the population surrounding all the junction points is spatially distributed over the study area, using the IDW tool in ArcGIS. Figure 3 shows the population surrounding the junction of the WDN of the study area and it is classified into five classes. The high population surrounding the junction is assigned a rank of 5 and the low population surrounding the junction is assigned a rank of 1, and the weights obtained for the population map using AHP is 26%, as given in Table 5.

Elevation

Elevation denotes the height of any object with respect to the assumed datum. In this study, elevation was considered as an important factor because when the elevation of the tank location increases, it subsequently increases the pressure in the pipes.

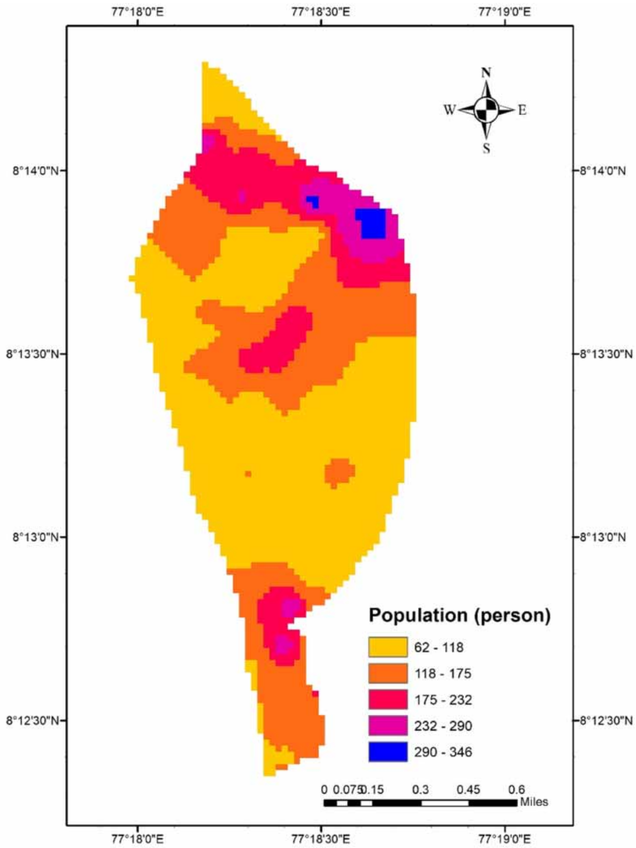

Figure 3 | Population map.

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Table 5 | List of factors with ratings and AHP weights

S. No.	Factors	Range	Rank	Weight	Weight in 100%
1	Elevation (m)	28–42	1	0.3555	36
		42–52	2		
		52–62	3		
		62–72	4		
		72–87	5		
2	Population	62–119	1	0.2617	26
		119–175	2		
		175–232	3		
		232–289	4		
		289–346	5		
3	Slope (percentage)	0–2.419	1	0.1778	18
		2.419–4.052	2		
		4.052–5.721	3		
		5.271–7.778	4		
		7.778–12.495	5		
4	Euclidean distance	0–0.000547	5	0.1207	12
		0.000547–0.00109	4		
		0.001094–0.001641	3		
		0.001641–0.002188	2		
		0.002188–0.002735	1		
5	Land use land cover	Agriculture/plantation/fallow	1	0.0843	8
		Built-up area	5		

The elevation of the current study area ranges from 28 to 87 m, which is classified into five classes, as shown in Figure 4. The tanks are generally located in high-elevated areas (Mays 2000)**.** Thus the highest rank of 5 is assigned for high elevation and the lowest rank of 1 is assigned for low elevation, as given in Table 5. The overall weight for the elevation obtained through AHP was 36%.

Slope

The slope of an area also influences the location of the water tank. A lower slope value indicates a flat slope, while a higher slope value indicates a steep slope. The tanks are to be located on a higher slope for sufficient pressure. The slope of the study area varies from 0 to 12.495%, which is classified into five classes as shown in Figure 5. The lowest rank of 1 is assigned for the lower slope and the highest rank of 5 is assigned for the higher slope, as given in Table 5. The overall weight for the slope factor as per AHP is 18%.

Distance to the road

Water supply pipelines are provided along the road networks. The road network in the study area consists of rural roads that are bituminous and concrete. The road map was created using polyline and the Euclidean distance (meter) was used to create the distance to the road from the tank in the ArcGIS environment. The Euclidean distance (meter) values range from 0 to 0.002735794, as shown in Figure 6. This is classified into five classes using the reclassify tool in ArcGIS. The lower values represent the distance nearer to the road and the higher values represent the distance away from the road. As per principle, the head required to drive the system probably increases with the increase in head loss. Since the head loss is directly proportional to the length of the pipe, the tank must be located nearer to the roads (Garg & Garg 2010). Thus, a rank of 5 is assigned to the Euclidean distance with a lower value and a rank of 1 is assigned to a higher Euclidean distance value, as shown in Table 5. The weight calculated using the AHP method is 12%.

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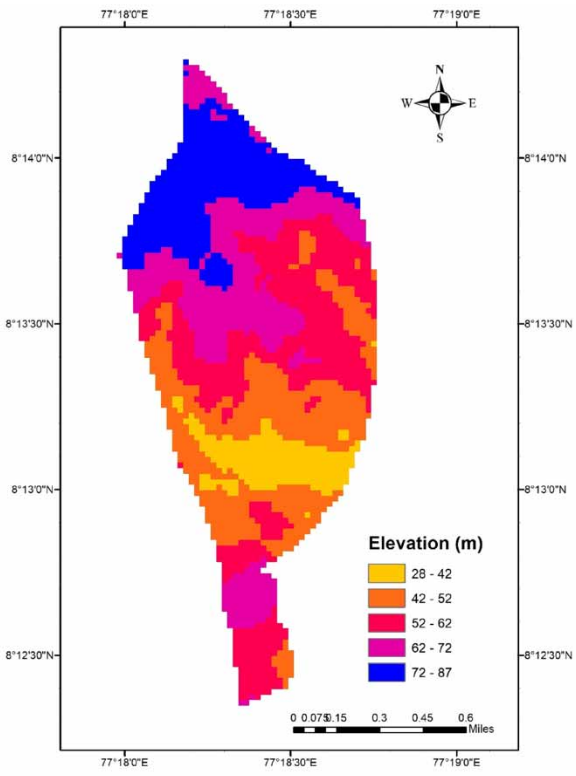

Figure 4 | Elevation map.

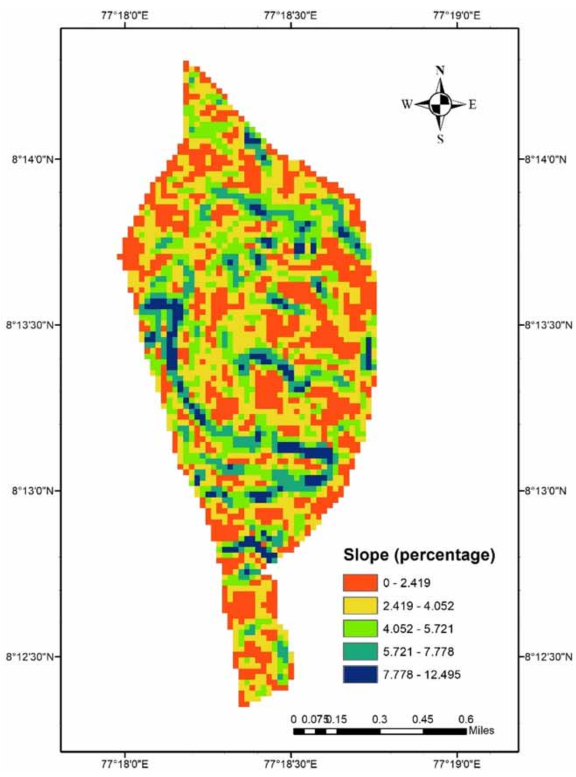

Figure 5 | Slope map.

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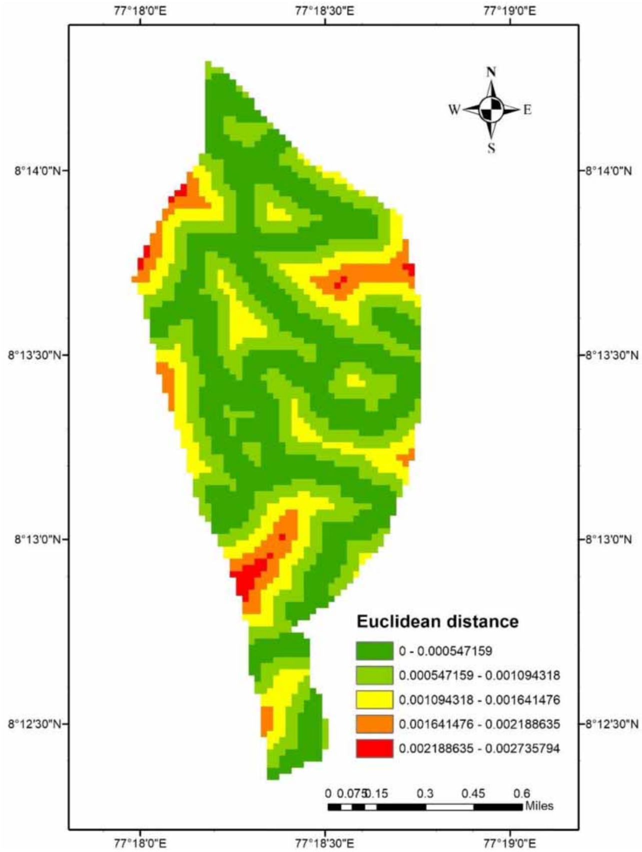

Figure 6 | Distance-to-road map.

Land use/Land cover (LULC)

Land cover denotes both natural and manmade coverings on the surface of the earth such as soil, topography, human structures, etc., while land use refers to the human usage of the biophysical attributes of the land for various purposes (Giri 2012). LULC was classified into three major classes: built-up area, agricultural area, and fallow land, as shown in Figure 7. The land use cover map of the study area consists of a built-up area of about 47%, an agricultural area of 51%, and a fallow land of 2%. The location of the tank must be situated near the high-demand areas (Mays 2000). The population is directly related to the built-up area, thus making the demand higher in built-up areas. Therefore, a higher rank of 5 is assigned to the built-up area, whereas a rank of 1 is assigned to the agricultural and fallow lands, as given in Table 5. The overall weight of the land use land cover map using AHP is 8%.

Location suitability map

The location suitability map of the study area was generated using the weighted overlay method in ArcGIS, which is shown in Figure 8. The location suitability map is classified into five different classes such as unsuitable, least suitable, moderately suitable, suitable, and highly suitable. From the results, it can be found that none of the areas corresponds to a highly suitable location as per Equation (3). About 15.69% of the total area is suitable for locating water tanks. They are found near regions having higher slope and elevation, high population, and nearer to roads. Majority of the area (52.36%) is moderately suitable and about 31.31% of the area is least suitable for locating water tanks. Only 0.63% of the area is not suitable for locating water tanks, which is near the region having an elevation range of 28–42 m (Zone II).

Validation of results using EPANET

For the performance study, a single-period simulation is carried out by considering the peak demand at the junctions in EPANET. Since the unsuitable location falls only in the small area of the study area, analysis is done in EPANET for suitable and least suitable locations, as shown in Figure 8.

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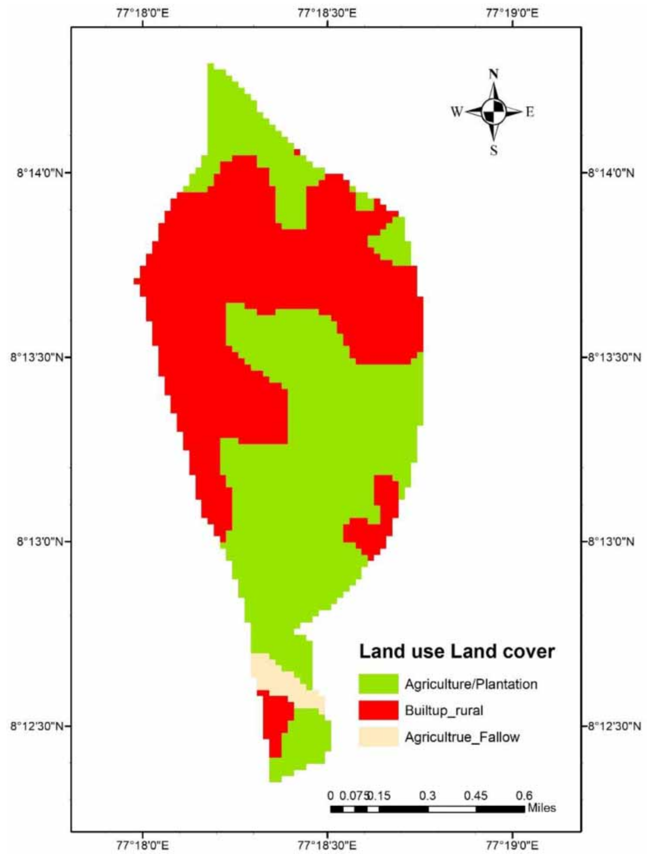

Figure 7 | Land use and land cover map.

From Figure 9, when the tanks are located at a suitable location, the pressure ranges from 9.77 m at junction J95 to 35.16 m at junction J59. However, when the tanks are placed at a least suitable location, negative pressures are created at the junctions J44, J45, J52, J66, J67, and J95. In the design of the WDN, the pipe size can be increased wherever pressure is less, and where pressure is higher, the pipe size can be decreased to equalize the flow (Wadkar & Mali 2007). However, increasing the diameters cannot increase the pressure in some junctions, which have a higher elevation than that of the elevation of the tank.

From Figure 10, it can be seen that when the tanks are located at suitable locations, the diameter varies from 50 to 250 mm, in which the majority of the pipes have diameters below 100 mm. However, when the tanks are located at the least suitable locations, the diameter varies from 50 to 250 mm, but the majority of the pipes have a diameter greater than 120 mm. Thus, it can be seen that the diameters of pipes decrease when the tanks are placed at suitable locations. Thus, the location of water tanks plays a vital role in maintaining the pressure and reducing the pipe size. Thus, by locating the tank in a suitable location, an effective design can be made.

DISCUSSION

The diameters of pipes have been the subject of numerous studies that have used heuristic algorithms or machine learning to solve their optimization problems. This study showed that the location of the water tank has a big impact on the successful design of a WDN. Water tanks are typically placed in very elevated places based on experience. As a result, in this study, AHP and GIS are used to determine a water tank's suitable site. This study consists of four major steps: (i) to identify the factors that affect the water tank's position, (ii) to determine the weights of the components using the AHP method, (iii) to develop a location suitability map using the ArcGIS overlay method, and (iv) to verify whether the location has an impact on the effective design (i.e., the decrease of pipe size). The results depend on the rank-based rankings produced by the AHP approach. As a result, the AHP method is significant in the assessment of factor weights. More factors could be taken into account in order

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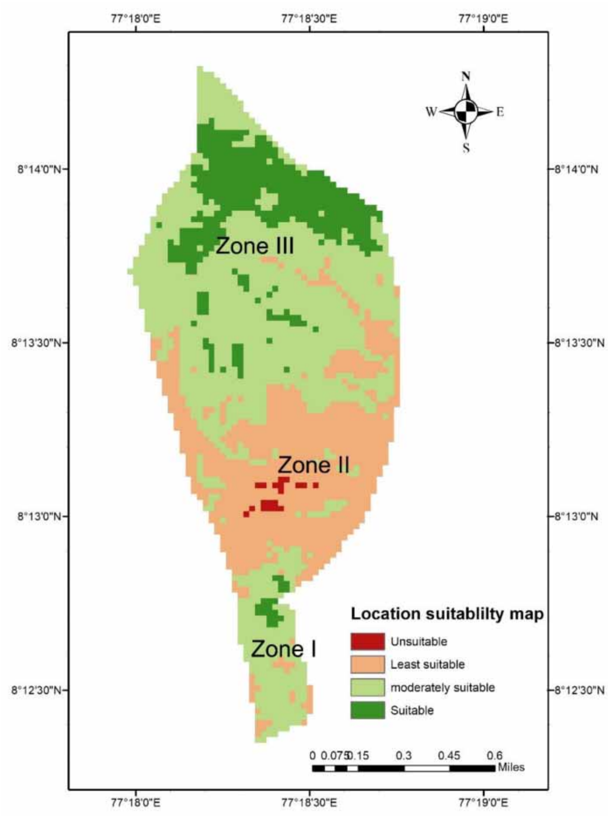

Figure 8 | Location suitability map.

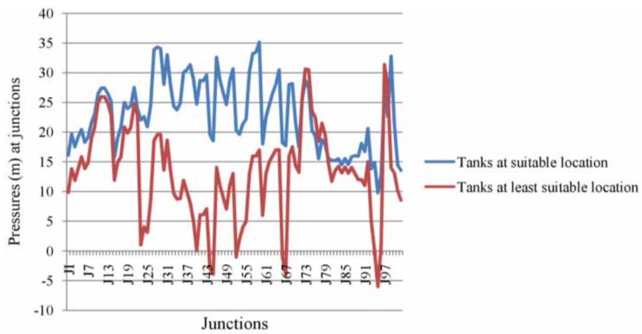

Figure 9 | Variations of pressures when tanks are at suitable and least suitable locations.

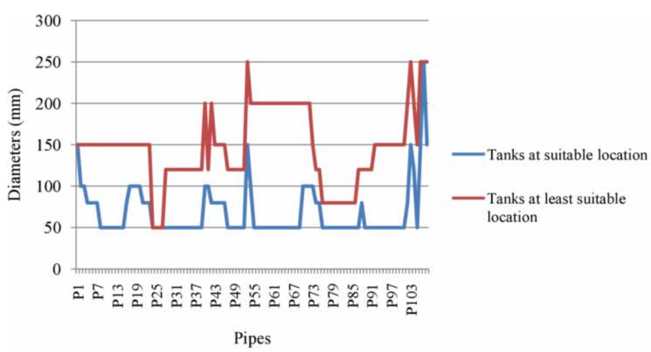

Figure 10 | Variations of diameters when tanks are at suitable and least suitable locations.

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to increase the study's accuracy. The results from this study proved that the location of water tanks plays an effective role in the effective design of the WDN, by reducing the pipe diameters significantly.

CONCLUSION

The use of GIS and AHP proves to be effective tools for identifying suitable tank locations. In this study, the thematic map layers of all the factors were created using ArcGIS, and the AHP technique was used to determine the normalized weights for the factors. The location suitability map of the water tanks was generated using a weighted overlay tool. They are classified into five classes: highly suitable, suitable, moderately suitable, least suitable, and unsuitable areas of water tank location. The results show that 15.69% of the area is suitable, 52.36% of the area is moderately suitable, about 31.31% of the area is least suitable, and 0.63% of the area is unsuitable for locating water tanks. None of the areas corresponds to a highly suitable location. The results are verified by placing tanks in suitable and least suitable locations, and an analysis was done using EPANET software. It can be concluded that locating water tanks in suitable locations reduces the size of pipes and maintains the pressure effectively. When the tanks are located in least suitable locations, the pipe size increases and a negative pressure is created at some junctions. Thus, the integration of AHP and GIS can help the designers to find suitable tank locations, and also, effective designs of the WDN.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 30 April 2023; accepted in revised form 11 August 2023. Available online 24 August 2023

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