American Journal of Water Resources, 2022, Vol. 10, No. 1, 17-23
Available online at http://pubs.sciepub.com/ajwr/10/1/3
Published by Science and Education Publishing
DOI:10.12691/ajwr-10-1-3

Groundwater Potential Recharge Zone Mapping for the Wolf River Watershed, Tennessee

Khairul Hasan[1,2], Sondipon Paul[2,*], Khayrun Nahar Mitu[1], Fuad Bin Nasir[3]

[1]Department of Civil & Environmental Engineering, Shahjalal University of Science and Technology, Sylhet, Bangladesh
[2]Department of Civil Engineering, The University of Memphis, TN, USA
[3]Department of Civil & Environmental Engineering, University of Wisconsin-Milwaukee, Wisconsin, USA
*Corresponding author: spaul1@memphis.edu

Received March 15, 2022; Revised April 17, 2022; Accepted April 28, 2022

Abstract The article presents groundwater potential recharge zone analysis in the Wolf River watershed applying the Geographic Information System (GIS) technique. Six thematic layers: elevation, slope, drainage density, rainfall, land cover, and soil type are prepared and integrated for the spatial analysis. The analysis applies the multi-criteria-based Analytical Hierarchy Process (AHP) to obtain each layer's weight. The thematic layers with the assigned weightage are overlain in a weighted overlay analysis to develop the study area's potential groundwater recharge zone map. Potential recharge zones are classified into four categories: very low, low, medium, and high. The result shows that the medium zone occupies a large portion of the watershed's central and southern regions. The study also reveals that the high and low zones cover a minimal watershed area. The findings can help policymakers make informed decisions for sustainable management of groundwater resources of the study area.

Keywords: *Geographical Information System (GIS), Analytical Hierarchy Process (AHP), Potential Groundwater Recharge Zone Mapping, Watershed Delineation, Weighted Overlay.*

Cite This Article: Khairul Hasan, Sondipon Paul, Khayrun Nahar Mitu, and Fuad Bin Nasir, “Groundwater Potential Recharge Zone Mapping for the Wolf River Watershed, Tennessee.” *American Journal of Water Resources*, vol. 10, no. 1 (2022): 17-23. doi: 10.12691/ajwr-10-1-3.

1. Introduction

Around 40 percent of the USA's public water supply utilizes groundwater [1]. Over the past decades, rapid population growth, urbanization, irrigation, and industrialization caused over-exploitation resulting in decreasing groundwater resources [2,3,4,5]. An equilibrium between groundwater extraction, water supply demand, water quality, and the natural replenishment of the aquifer is essential. Although surface water (rivers, lakes, dams) and irrigated water contribute to groundwater recharge [4], infiltration of the precipitated water is the primary groundwater recharge source. Therefore, investigating the potential groundwater recharge zones and preparing a protection plan is critical for the sustainable management of groundwater resources.

Numerous studies applied geological formation and hydrological properties to delineate the potential groundwater recharge zones [6,7,8,9]. The prior works suggest lithology, drainage density, lineament density, land use, rainfall, soil type, elevation, and ground slope as the primary parameters for the delineation [8,10]. Geospatial techniques are commonly used to integrate the parameters since these techniques are swift and cost-efficient [5,6,7,8,9]. Of the geospatial techniques, Analytical Hierarchy Process (AHP) integrated with Geographical Information System (GIS) is efficient for groundwater exploration and potential recharge zone mapping [6,8,10,11,12]. AHP is suitable for multi-criteria problems like the potential recharge zone delineation because it assigns and calculates each thematic layer's weight for the overlay analysis for the delineation [8].

This article presents potential groundwater recharge zone delineation for the Wolf River watershed, Memphis, Tennessee. We apply the AHP and GIS techniques to evaluate the potential recharge zones inside the delineated watershed. The study findings can help policymakers formulate and implement various regulations to ensure groundwater recharge in the Memphis area. The described technique can also help find future groundwater development locations for the city's water supply.

2. Study Area and Data Used

The Wolf River rises in the Holly Springs National Forest, Mississippi. It drains a large portion of Memphis and Shelby County, Tennessee, before discharging into the Mississippi River near downtown Memphis [13]. In this paper, we delineated the Wolf River watershed based on the stream gage USGS 07031650. The gaging station acted as the outlet for the watershed. The elevation data for the study area were obtained from Digital Elevation Model (NED10m) retrieved from the national map data download and visualization services at 1/3 arc-second. As shown in Figure 1, the subsequent geoprocessing analysis steps were performed following the data acquisition while delineating the watershed. Figure 2 shows the delineated watershed with stream order based on a hierarchy of tributaries. The watershed has a total drainage area of 1805.74 sq. km. Table 1 lists all the relevant data sets with their corresponding source to prepare the thematic maps for the study area. All the thematic layers were projected to the NAD 1983 UTM Zone 16N.

Table 1. List of collected data with corresponding sources

Data type	Source
Digital Elevation Models	The National map data download and visualization services at 1/3 arc-second (approximately 10 m)
Land use/land cover	NLCD 2016 Land Cover (CONUS) at 30 m resolution based on a modified Anderson Level II classification system
Soil Map	FAO-UN-Land and Water Division
Rainfall map	CRU monthly climate dataset

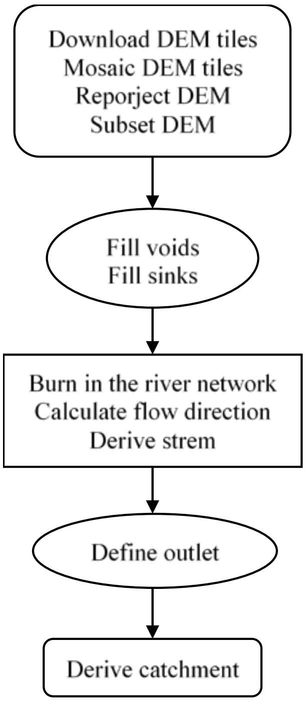


Figure 1. Workflow for stream and watershed delineation

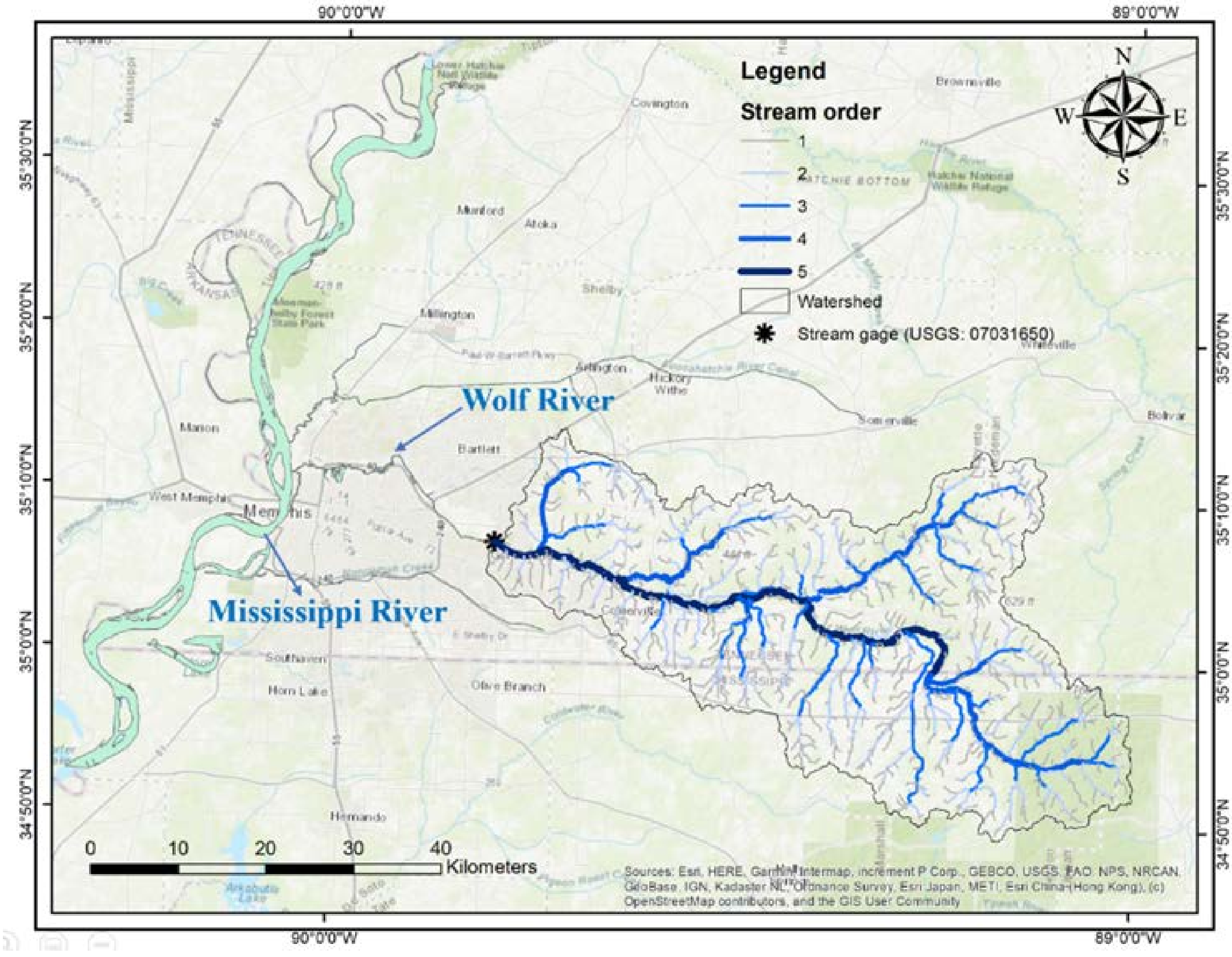


Figure 2. The Wolf River watershed delineated under this study based on the stream gage USGS 07031650

3. Methodology

The selection of contributing factors to identify potential groundwater recharge zones depends on insight and data availability [6]. This work selected elevation, slope, drainage density, rainfall, land cover, and soil type as the contributor to the mapping due to their availability. We developed a pairwise comparison matrix using Analytical Hierarchy Process (AHP) to find the weights for each influencing factor [6,14]. Table 2 presents a pairwise comparison scale ranging from 1 to 9, as Saaty (1990) [15] described. The weights for each thematic layer were verified using the consistency ratio (CR). If the CR value is less than or equal to 0.10, the comparison matrix is consistent [8,10,15]. Table 3 lists the pairwise comparison and weights of thematic layers with a CR value of 0.08.

All six thematic layers were integrated with the weighted overlay analysis for the wolf river watershed using Eqn. 1 [14]. We classified the obtained groundwater potential zones into four categories: very low, low, medium, and high potential zones. Figure 3 shows the flowchart that summarizes the different steps followed in this work.

$$GWPZ = \sum W_i * X_i \quad (1)$$

Where, GWPZ = groundwater potential zone; W_i = weight for each thematic layer; X_i = individual map.

Table 2. Scale of relative importance (Source: Saaty (1990) [15])

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another. Its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8 can be used to express intermediate values		

Table 3. Pairwise comparison and weight assignment using the AHP process

a

		Criteria		More important?	Scale
i	j	A	B	A or B	(1-9)
1	2	Rainfall	Soil type	A	1
1	3		Drainage density	A	3
1	4		Slope	A	5
1	5		Land cover	A	5
1	6		Elevation	A	5
2	3	Soil type	Drainage density	A	1
2	4		Slope	A	5
2	5		Land cover	A	1
2	6		Elevation	A	3
3	4	Drainage density	Slope	A	3
3	5		Land cover	A	3
3	6		Elevation	A	3
4	5	Slope	Land cover	B	3
4	6		Elevation	A	1
5	6	Land cover	Elevation	A	5

b

No	Criteria	Weights (per cent)	+/- (percent)
1	Rainfall	36.4	18.5
2	Soil type	20.3	7.7
3	Drainage density	19.2	9.9
4	Slope	5.1	1.1
5	Land cover	13.8	7.0
6	Elevation	5.2	1.5

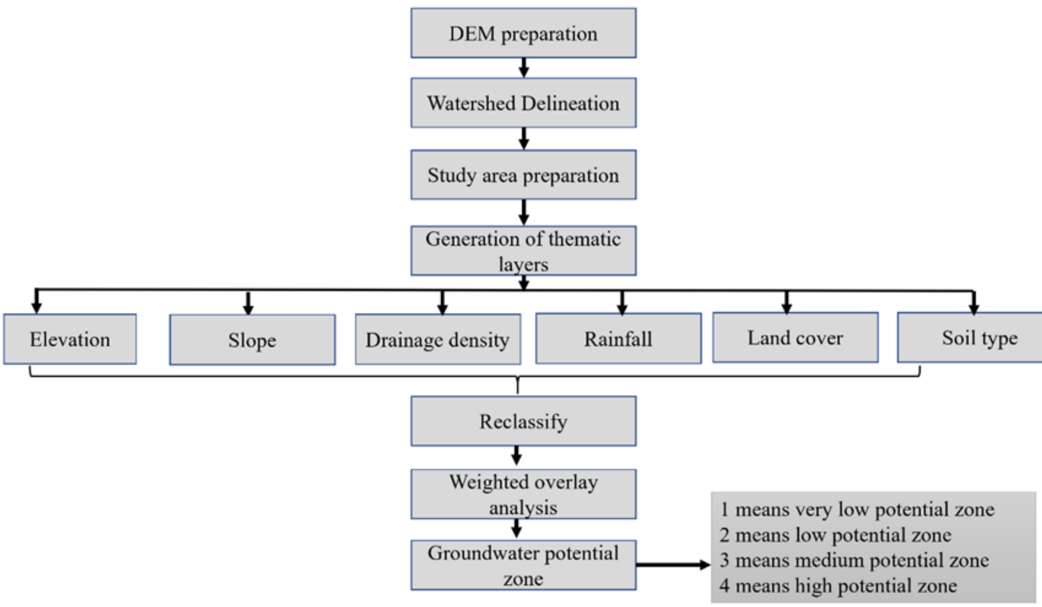


Figure 3. Flowchart for delineating the potential groundwater recharge zone

4. Results and Discussions

We classified six thematic maps of elevation, slope, drainage density, rainfall, land cover, and soil type, and weighted them to delineate the potential groundwater recharge zone. The elevation layer depicts the ground surface undulations available for precipitated water retention [8]. The areas with lower elevation offer sufficient resident time for the precipitated water to infiltrate, indicating a higher potential recharge zone. Figure 4 shows the elevation maps classified into four categories. The green areas indicate a low elevation and get the highest score in the reclassified map.

The land surface slope is also a critical factor affecting surface runoff and infiltration [16]. Areas with steep slopes expectedly generate more runoff resulting in a low infiltration potential [6,7]. Therefore, this work considers steep areas as low potential recharge zone. The slope values are reclassified into four categories again, where red areas denote a steep slope. Figure 5 shows the slope map of the Wolf River watershed where the red regions receive the lowest score.

The drainage density of an area inversely affects soil permeability that influences the overall infiltration rate of the area. Higher drainage density increases surface runoff resulting in a lower infiltration of precipitated water [10]. We calculated the drainage density for the studied area by dividing the stream's total length in the delineated watershed by its total area [7,10]. Red marked regions in Figure 6 indicate the highest drainage density areas in the Wolf River watershed, and thereby, we assign the lowest rating score to it.

As the only source of groundwater recharge, rainfall is the most influential factor in mapping a region's potential recharge zones [8,10]. A higher rainfall distribution can increase infiltration potential resulting in a higher recharge to the aquifer. This work interpolates the annual average rainfall data of 2016 by applying the Kriging method to obtain the spatial distribution map of precipitation. The areas with higher rainfall marked as green are assigned the highest score in the reclassified map, as shown in Figure 7.

The land cover thematic map is another decent indicator for quantifying recharge, runoff, and infiltration [17]. We use a land-use map for 2016 developed by the U.S. Geological Survey [18], as shown in Figure 8 for the land cover thematic map generation. We assign different land-use areas with different scores for the weighted overlay analysis based on the infiltration and water runoff capacities. The open water body and cultivable land having the highest groundwater potential receive the highest score in this work. Likewise, the agricultural and the forest lands get a medium score in the weighted overlay analysis. In contrast, buildings and barren land having lower infiltration capacity get the lowest score.

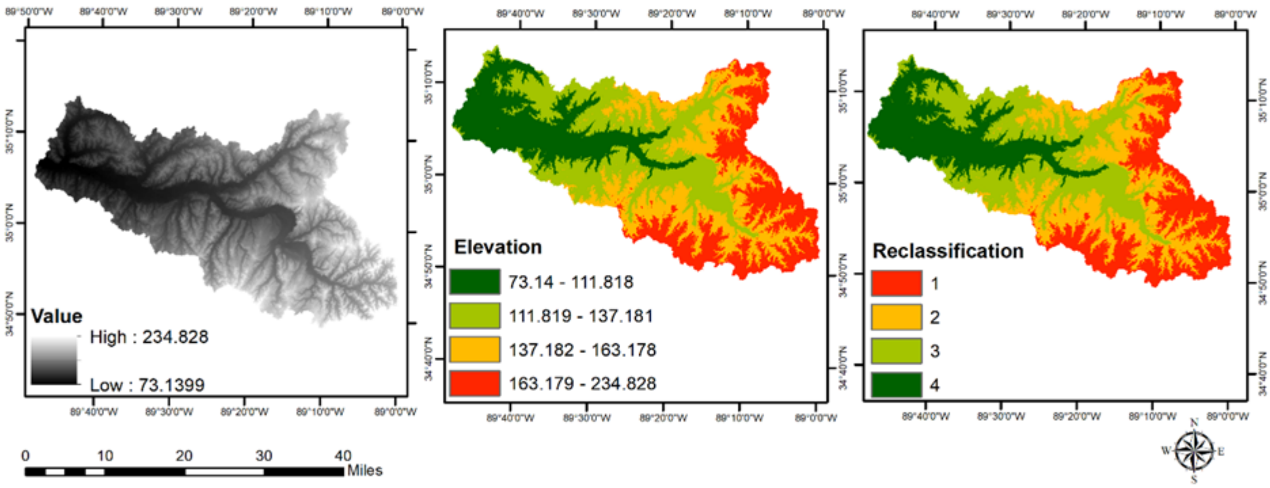


Figure 4. Elevation map of the study area

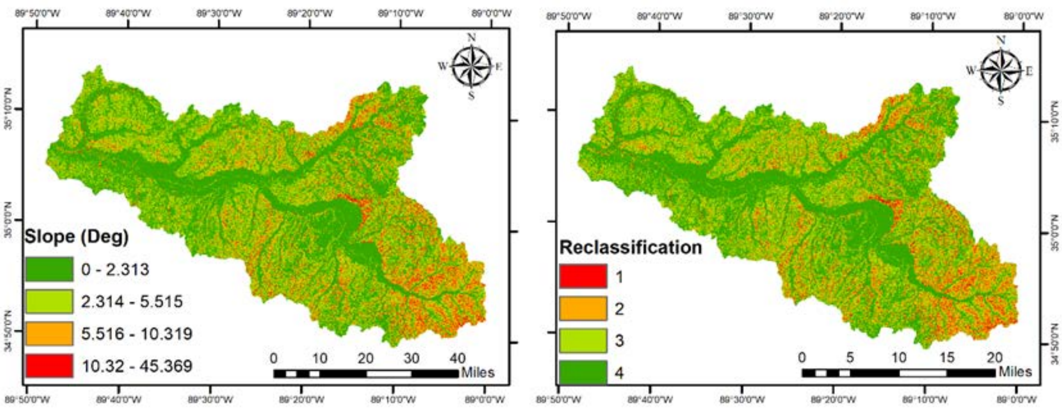


Figure 5. Slope map of the study area

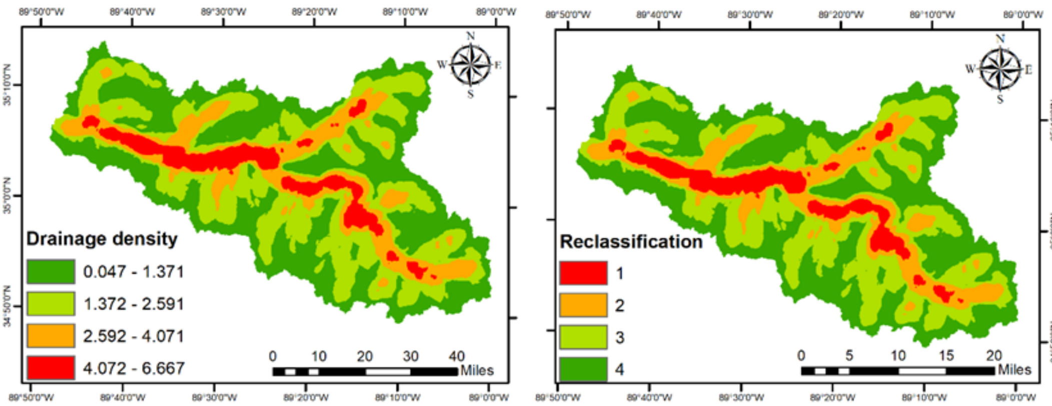


Figure 6. Drainage density map of the study area

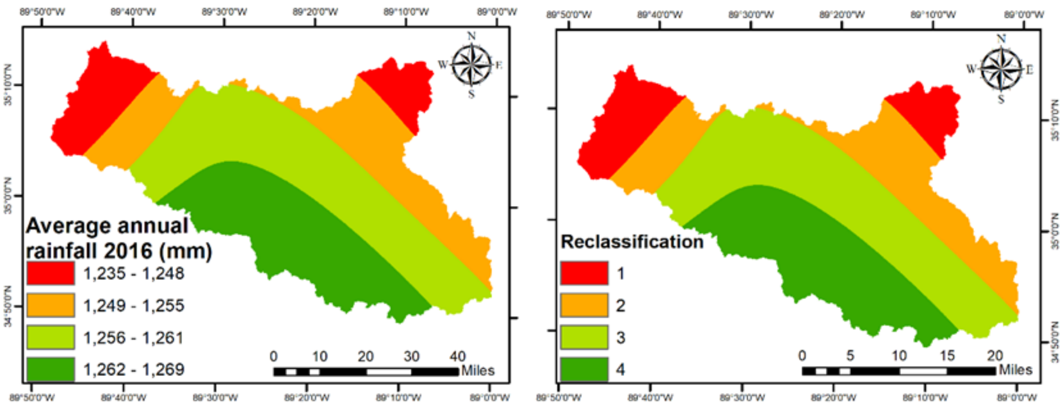


Figure 7. Rainfall map of the study area

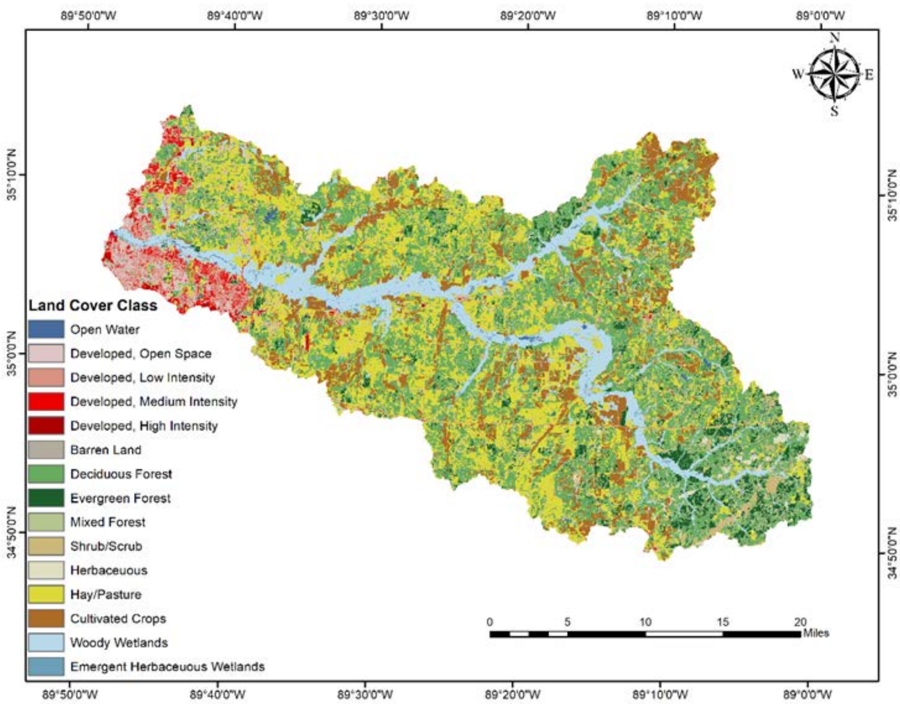


Figure 8. Land use map of the study area for 2016 (source: Jin et al. (2019) [18])

We also use soil texture classes called hydrological soil groups (HSGs) provided by the U.S. Department of Agriculture (USDA). The data set has a resolution of 250 meters. The data set indicates two major soil types in the Wolf River watershed: HSG-C and HSG-C/D, as shown in Figure 9. HSG-C soil type has a high runoff potential, therefore, gets the lowest score.

The groundwater potential recharge zone map developed under this work is presented in Figure 10. The map suggests that the potential recharge zone follows the rainfall distribution in the Wolf River watershed. The northwest of the watershed shows a very low to low potential for groundwater recharge. Urbanization and low rainfall in this part of the watershed support our findings. The map also depicts the northeast of the watershed as having low recharge potential due to comparatively less rainfall, steep slope, higher elevation, and denser drainage. The presence of higher drainage in the vicinity of the Wolf River illustrates a potentially low recharge along the center of the watershed. In contrast, the south and north-central areas of the watershed exhibit a medium potential for groundwater recharge. Gentle slope, low elevation, and comparatively higher rainfall are the primary contributing factors defining a higher potential for infiltration of the precipitated water in these areas. The study also finds very few areas with a high groundwater recharge potential to the south of the watershed.

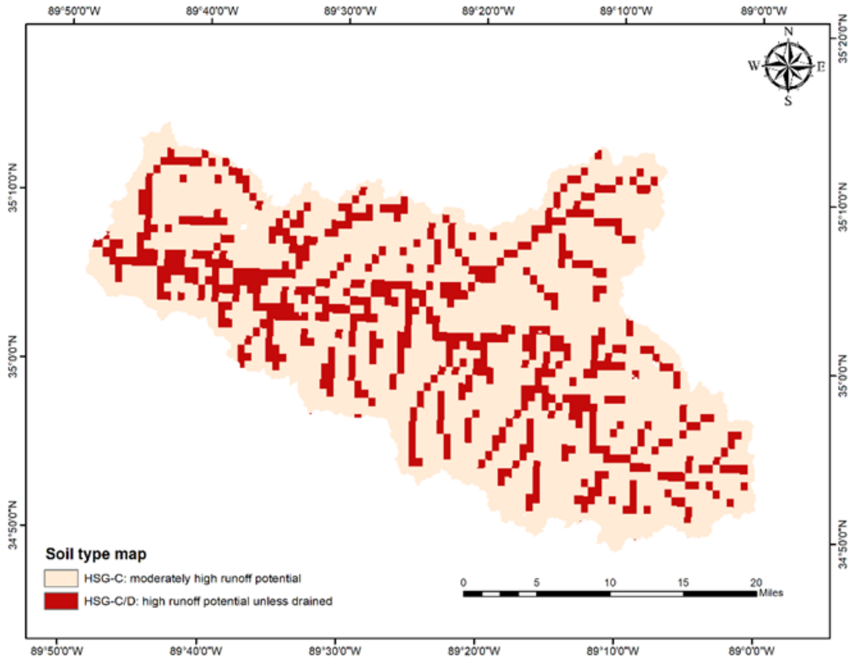
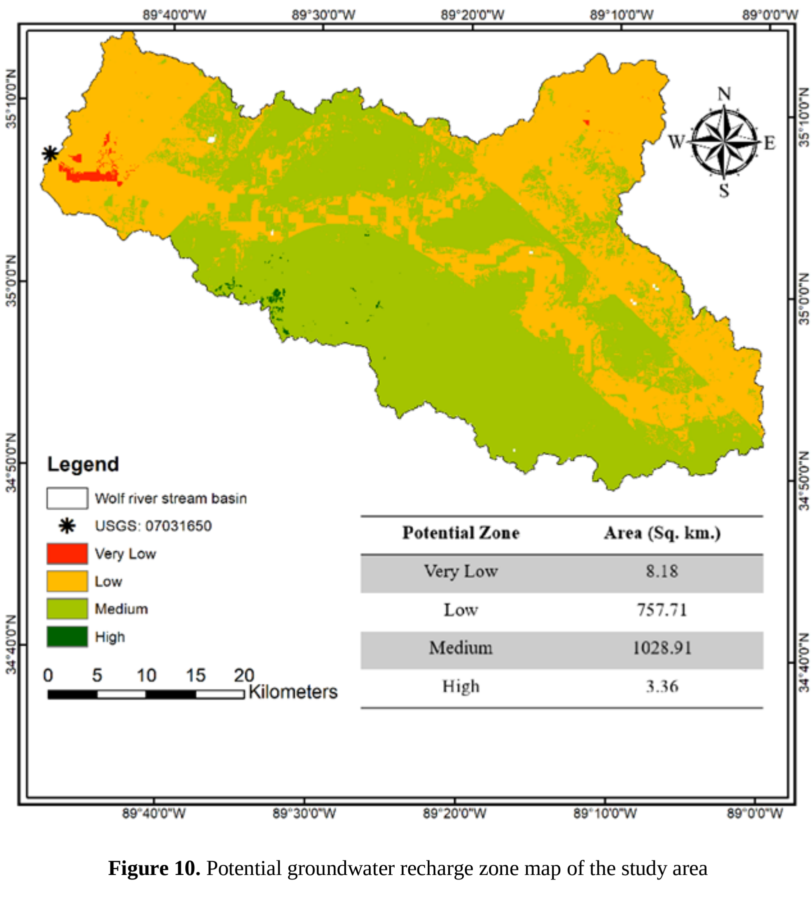


Figure 9. Soil map of the study area



Potential Zone	Area (Sq. km.)
Very Low	8.18
Low	757.71
Medium	1028.91
High	3.36

Figure 10. Potential groundwater recharge zone map of the study area

5. Conclusion

The study applied two widely used tools, Analytical Hierarchy Process (AHP) and Geographical Information System (GIS), to delineate the potential groundwater recharge zones for the Wolf River watershed in western Tennessee's Memphis area. Six thematic layers of elevation, slope, drainage density, rainfall, land cover, and soil type were weighted with appropriate scores. This work's potential groundwater recharge map divided the Wolf River watershed into four subregions: very low, low, medium, and high recharge potential zones. The results indicated that the watershed's northwest and northeast areas are very low recharge potential zone. In contrast, the watershed's north-central and southern regions exhibited the medium potential for groundwater recharge. A few areas also showed high and very low potential for groundwater recharge located to the south and west of the watershed.

The study's primary limitation is the lack of verification of the obtained results from the potential zone map with the watershed's observed groundwater levels. The verification by drilling new boreholes is also out of the scope of the present study. The results indicated that the rainfall distribution heavily influenced the potential groundwater zones. Since the current work only used annual average rainfall data for 2016, comparing the groundwater potential zone maps developed for five-year intervals can help identify the zones more precisely. Nevertheless, this study provides an insight for the decision-makers and scientists working in this study region to help manage and develop its groundwater resources in a sustainable manner.

Declaration of Competing Interest

The authors declare that there is no competing interest in this paper.

Acknowledgments

The authors acknowledge the research contributions of all the citations under reference.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Alley, W.M., Reilly, T.E., Franke, O.L., 1999. Sustainability of groundwater resources. U.S. Department of the Interior, U.S. Geological Survey.

[2] Hall, N.D. and Regalia, J., 2016. Interstate Groundwater Law Revisited: Mississippi v. Tennessee. Virginia Environmental Law Journal, 34(2), pp.152-203.

[3] Ahmadi, H., Kaya, O. A., Babadagi, E., Savas, T., & Pekkan, E., 2020. GIS-Based Groundwater Potentiality Mapping Using AHP and F.R. Models in Central Antalya, Turkey. In Environmental Sciences Proceedings (Vol. 5, No. 1, p. 11). Multidisciplinary Digital Publishing Institute.

[4] Paul, S., Hasan, K., 2021. The impact of the proposed rubber dam facilitated surface water irrigation on adjacent groundwater at Chapai Nawabganj district, Bangladesh. Appl Water Sci 11, 36 (2021).

[5] Hasan, K., Paul, S., Chy, T.J., Antipova, A., 2021. Analysis of groundwater table variability and trend using ordinary kriging: the case study of Sylhet, Bangladesh. *Appl Water Sci*. 11, 120 (2021).

[6] Al-Djazouli, M.O., Elmorabiti, K., Rahimi, A., Amellah, O., Fadil, O.A.M., 2020. Delineating of groundwater potential zones based on remote sensing, GIS and analytical hierarchical process: a case of Waddai, eastern Chad. GeoJournal. 1-14.

[7] Magesh, N.S., Chandrasekar, N., Soundranayagam, J.P., 2012. Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosci. Front. 3, 189-196.

[8] Saranya, T., Saravanan, S., 2020. Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. Model. Earth Syst. Environ. 6, 1105-1122.

[9] Yeh, H.-F., Cheng, Y.-S., Lin, H.-I., Lee, C.-H., 2016. Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan. Sustain. Environ. Res. 26, 33-43.

[10] Arulbalaji, P., Padmalal, D., Sreelash, K., 2019. GIS and AHP Techniques Based Delineation of Groundwater Potential Zones: a case study from Southern Western Ghats, India. Sci. Rep. 9, 2082.

[11] Benjmel, K., Amraoui, F., Boutaleb, S., Ouchchen, M., Tahiri, A., Touab, A., 2020. Mapping of Groundwater Potential Zones in Crystalline Terrain Using Remote Sensing, GIS Techniques, and Multicriteria Data Analysis (Case of the Ighrem Region, Western Anti-Atlas, Morocco). Water 12, 471.

[12] Kaliraj, S., Chandrasekar, N., & Magesh, N. S., 2014. Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. Arabian Journal of Geosciences, 7(4), 1385-1401.

[13] Kesler, D. H. (2004). Influence of a Lentic Area on Condition Indices of Corbicula flumineain the Wolf River, Tennessee. Journal of Freshwater Ecology, 19(3), 445-453.

[14] Adeyeye, O.A., Ikpokonte, E.A., Arabi, S.A., 2019. GIS-based groundwater potential mapping within Dengi area, North Central Nigeria. Egypt. J. Remote Sens. Space Sci. 22, 175-181.

[15] Saaty, T.L., 1990. Decision making for leaders: the analytic hierarchy process for decisions in a complex world. RWS publications.

[16] Magesh, N.S., Chandrasekar, N., Soundranayagam, J.P., 2011. Morphometric evaluation of Papanasam and Manimuthar watersheds, parts of Western Ghats, Tirunelveli district, Tamil Nadu India: A GIS approach. Environ. Earth Sci. 64, 373-381.

[17] Shaban, A., Khawlie, M., & Abdallah, C., 2006. Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. Hydrogeology Journal, 14(4), 433-443.

[18] Jin, S., Homer, C., Yang, L., Danielson, P., Dewitz, J., Li, C., Zhu, Z., Xian, G., Howard, D., 2019. Overall methodology design for the United States national land cover database 2016 products. Remote Sens. 11, 2971.