



GeoSpatial Identification of Artificial Groundwater Recharge Locations by Rainfall using Analytical Hierarchy Process in Samarkand City

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Abstract

The Samarkand city is located on the left bank of the Zarafshan River. However, the city experiences an acute crisis of water due to rapid socio-economic development and population growth, resulting in increasing water demand. A heavy reliance on groundwater was made to meet these water demands, leading to its overexploitation and resulting in a significant decline in groundwater levels, which requires urgent attention to explore potential mediums for replenishing the groundwater. The current study focuses on the potential rainwater harvesting and artificial recharge zones by analyzing the seven variables like geology, soil types, land use and land cover, slope, curvature, drainage density, and distance from lineaments. The potential artificial recharge locations for rainwater harvesting and artificial recharge are identified by employing the analytical hierarchy process (AHP) using a geographic information system (GIS). The highest scores (ranked good), indicate the most suitable locations for rainwater harvesting and artificial recharge, covering an area of about 10 km² (18.9%). Recharge can be made during rainfall events, where relatively large volumes of water become available relatively quickly and accumulate at surface depressions. The runoff can be stored in groundwater by enhancing its infiltration through gravity injection wells. The weighted overlay method was implemented to identify potential rainwater harvesting and artificial recharge locations using seven parameters: geology, soil type, land use and land cover, slope, curvature, drainage density, and distance from lineaments.

Keywords: analytical hierarchy process (AHP), artificial recharge, GIS, groundwater, rainwater harvesting, Samarkand city, weighted overlay method

1. INTRODUCTION

Water resources in the Republic of Uzbekistan are under significant stress due to the country's location within an arid climatic zone, where surface and groundwater availability are inherently limited. Since gaining independence, Uzbekistan has experienced a profound socio-economic transformation, influenced primarily by rapid population growth and accelerated urbanization. These dynamics have placed additional pressure on the already scarce water resources, highlighting the urgent need for integrated and sustainable water management strategies. These developments have substantially increased water demand across multiple sectors, leading to groundwater abstraction

rates that exceed the natural recharge capacity [1]-[3]. Uzbekistan's territorial structure consists of peneplains divided into regions, major cities, sub-districts, and rural settlements. Key urban centers include Tashkent, Samarkand, Bukhara, Andijan, Namangan, Navoi, Termez, and Nukus. Samarkand is among Central Asia's oldest continuously inhabited cities, distinguished by its rich historical legacy and internationally recognized cultural landmarks [4]-[6]. In recent decades, Samarkand has emerged as a prominent tourist destination, driving rapid socio-economic development in the region [7][8]. However, socio-economic growth has also led to the overexploitation of groundwater resources. The prolonged drought from 1998 to 2001 further intensified this trend, prompting a shift in water resource management, as groundwater began to be viewed as a practical alternative to diminishing surface water supplies [9][10]. In response to the drought's impacts, the Government of Uzbekistan enacted a special decree to mitigate its consequences, which included drilling approximately 2,600 shallow wells to meet rising water demands [9][11][12]. Following this initiative, many farmers with sufficient financial means began exploiting groundwater resources for irrigation, primarily to sustain crop production

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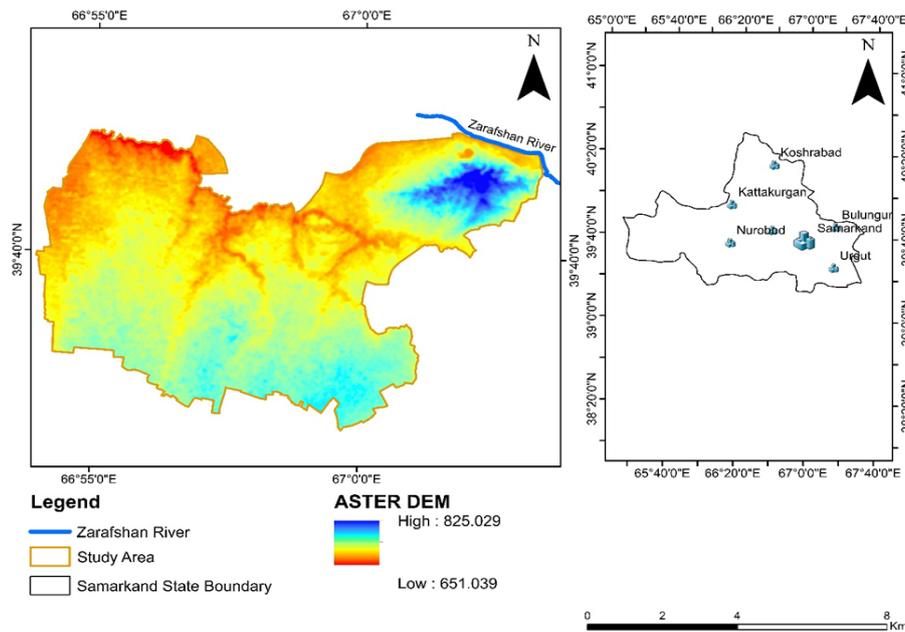


Figure 1. The spatial derivation of elevation and boundary of the study area with Samarkand Region administrative boundary.

during periods of reduced surface water flow and to ensure that the salinity levels of irrigation water remained within agriculturally acceptable limits [13].

Furthermore, World Bank projections estimate that by 2050, water availability in the Syrdarya basin may decrease by 2–5%, while the Amudarya basin could experience a more substantial reduction of 10–15%. These declines could lead to a decrease in regional GDP by up to 11%, with uncoordinated water use contributing to annual economic losses estimated at a minimum of \$1.75 billion [14]. The Cabinet of Ministers, local authorities, and relevant sectoral agencies primarily manage water governance in Uzbekistan. The Ministry of Water Resources oversees surface water, while the State Committee of Geology manages groundwater resources. Uzbekistan has implemented institutional and legal reforms to enhance the management and protection of water resources. Notably, Law No. 733, enacted on November 30, 2021, amended the existing "Law on Water and Water Use," thereby extending the authority of the Cabinet of Ministers to promote the efficient use of water, address water shortages, support the adoption of water-saving technologies, and approve related strategic programs [15][16].

Samarkand, the second-largest city in Uzbekistan

with a population of approximately 550,000; currently faces an annual water demand of 29 million m³. This demand is projected to rise by 51%, reaching 44 million m³ by 2050, primarily driven by population growth and urbanization [17]. In response to incoming pressure, the water authorities in Samarkand have adopted the major water supply augmentation programs starting from 2018 (on measures to improve the efficiency of water resources use). This shift was reflected in the development of non-conventional water resources and the expansion of municipal wastewater treatment infrastructure throughout the city. Such alternative water supplies serve both municipal and agricultural sectors, helping to mitigate increasing demand [18]. To support long-term water security, sustainable groundwater management strategies have been structured around two core approaches: demand-side management and supply-side engineering interventions [19]. In Samarkand, Uzbekistan, agriculture dominates water use, consuming about 90% of resources due to extensive irrigation of crops like cotton and cereals. Only 23.0% of farmland uses water-saving technologies, highlighting inefficiencies. Domestic use accounts for 4.5%, with drinking water coverage rising from 54.6% to 73.1%, aiming for 92.5% by 2028. Industry and energy use 1.4%, though water

pumping consumes 8 billion kWh annually. Fisheries use 1.2%. This distribution reveals a pressing need for more sustainable water management, especially in agriculture. Addressing the challenges associated with groundwater overexploitation requires a comprehensive management strategy that targets both the reduction of demand and the augmentation of supply. Demand-side measures aim to regulate and reduce groundwater abstraction through strategic policies, technologies, and practices that optimize water use. In contrast, supply-side strategies enhance groundwater availability, primarily through water harvesting and storage augmentation. A central focus of this study is artificial aquifer recharge—a proven supply-side technique particularly suited to arid and semi-arid regions. Within an integrated water resources management framework, artificial recharge contributes significantly to restoring groundwater balance. Unlike infrastructure-based supply expansions, demand-side water management emphasizes efficient, equitable, and sustainable use of existing resources [20][21]. Furthermore, aquifer recharge methods are increasingly being recognized as essential components of sustainable water management projects in water-scarce environments [22][23]. Groundwater recharge can be achieved through various methods, including diverting water to large spreading basins that facilitate infiltration into underlying aquifers, employing injection wells to directly introduce water into the subsurface, or temporarily impounding water within river channels using inflatable or check dams to enhance natural

percolation [21][24][25]. Scientific literature demonstrates that numerous studies have been undertaken to determine optimal sites for artificial recharge and water harvesting in arid and semi-arid regions globally.

The spatial complexity of these investigations and the multitude of influencing factors, such studies commonly utilize geographic information systems (GIS) in conjunction with multi-criteria decision-making methodologies. These approaches enable the identification of suitable locations based on predefined criteria and the evaluation of relevant biophysical and hydrological parameters. Within the framework of multi-criteria decision-making, a range of analytical techniques has been employed to identify suitable sites for artificial recharge and water harvesting. Among the most commonly utilized methods are the weighted overlay analysis [26]-[29], the Fuzzy Logic Model [30][31], the Fuzzy C-Means Model [31][32], and the Boolean Logic Model [29][30][32][33][34]. These methods facilitate spatial decision-making by integrating multiple hydrological, geological, and socio-environmental parameters. Within the weighted overlay analysis, the weights of the parameters are assigned based on two techniques: an analytical hierarchy process (AHP) [28][34][35] and the multi-influencing factor [27][36]. In arid regions, researchers commonly use several key factors to identify the best locations for rainwater harvesting and artificial recharge. These include, in order of importance: slope, soil infiltration capacity, land use and land cover, geological features like

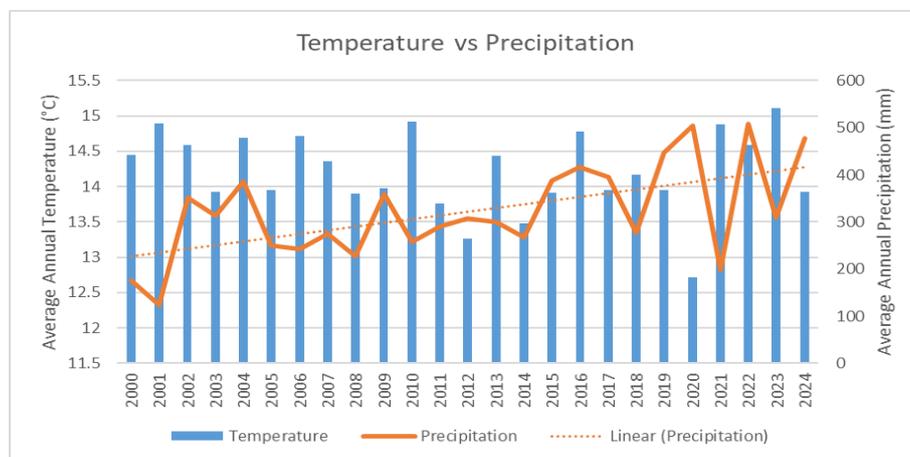


Figure 2. Recorded average annual precipitation & average annual temperature for the period 2000–2024 (Meteorological Directorate 2025).

Table 1. The selected parameters and their weightage for further analysis [55].

Parameters	Weightage (%)	Factors Affecting in Arid Regions
Soil Types	26%	Affects runoff, evapotranspiration, and infiltration
Geology	20%	Steepness affects infiltration time and runoff speed
LULC	19%	Key determinant of infiltration in water-scarce zones
Slope	13%	Controls permeability and storage of infiltrated water
Drainage Density	9%	Reflects runoff concentration; low density favors recharge
Distance from Lineaments	8%	Enhances subsurface flow if connected to recharge zones
Curvature	5%	Minor but relevant for micro-water accumulation

Table 2. The selected parameters and their rank categorization.

Slope (In degrees)		Curvature		Lineaments		Drainage Density	
Values	Ranks	Values	Ranks	Values	Ranks	Values	Ranks
0.0-0.10	5	-6.093 – -0.907	1	0–120	5	0.0–0.52	1
0.10-2.50	4	-0.907 – -0.259	2	120–258	4	0.52–1.50	2
2.50-4.00	3	-0.259 – 0.259	3	258–459	3	1.50–2.46	3
4.00-6.00	2	0.259 – 1.037	4	459–760	2	2.46–3.47	4
6.0-40.00	1	1.037 – 11.149	5	760–1549	1	3.47–5.79	5

fractures and joints (lineaments), geomorphology, aquifer properties, and groundwater depth. In Samarkand, where groundwater plays a vital role in meeting growing water demands and acts as a critical reserve during emergencies, enhancing groundwater through rainfall-based artificial recharge offers significant potential. However, this approach has not yet been implemented in the region. If practiced effectively and in suitable sites, it could help increase groundwater storage, improve its quality, and protect the aquifer from further depletion. This research aims to contribute to the effective and sustainable management of groundwater resources in Samarkand by identifying potential surface locations for groundwater artificial recharge by rainfall using AHP and GIS techniques.

2. MATERIALS AND METHODS

2.1. Study Area

Samarkand city is geographically positioned between 39° 37' 00'' N and 39° 42' 00'' N latitude and 66° 54' 00'' E & 67° 03' 00'' E longitude, with an elevation of 702 meters above sea level and a total area of approximately 68.42 km². Located in the southeastern part of Uzbekistan, Samarkand city is among the oldest continuously inhabited cities in

Central Asia. It is situated within the central Zarafshan Valley, bounded to the south by the foothills of the Pamir-Alay Mountain system and to the north by the Kyzyl-Kum Desert. However, the study area is located on the right bank of the Zarafshan river valley. From a geological perspective, the study area lies within the southern Tien Shan fold-and-thrust belt, a structurally complex zone shaped by prolonged tectonic processes including continental collisions, sedimentation, and crustal uplift. The subsurface geology comprises ancient metamorphic rocks such as schists and gneisses of Precambrian to Paleozoic age, which constitute the regional basement complex. The surrounding foothills and mountainous terrains expose a diverse lithology dominated by sedimentary and volcanic sequences, including limestones, sandstones, and volcanic rocks, indicative of deposition in shallow marine environments. These units experienced significant deformation during the Hercynian orogeny, approximately 300 million years ago. Overlying these Paleozoic formations are Mesozoic continental sandstones and shales, which in turn are capped by extensive Neogene to Quaternary alluvial, fluvial, and loess deposits that characterize the more recent geologic history of the region

(Figure 1).

The city is situated on the left bank of the Zarafshan River, with recent urban expansion extending to the right bank. The surrounding landscape features mountainous terrain to the east and north, composed of uplifted Paleozoic and Mesozoic formations. In contrast, extensive alluvial plains formed by the Zarafshan River dominate the central area and support intensive agriculture. Wind-deposited loess and eroded badlands characterize the southern and western margins. Groundwater in the Samarkand region is hosted within Quaternary alluvial deposits and Paleozoic bedrock. Shallow, unconfined aquifers occur in loess and alluvial sediments, recharged by precipitation and river infiltration, while deeper confined aquifers are found in fractured Mesozoic and Cenozoic sandstones and conglomerates. Samarkand has a semi-arid climate (Köppen BSk) with pronounced seasonal precipitation. Annual rainfall averages 350–400 mm, mostly occurring from November to April, peaking in March–April, and accounting for over 70% of the yearly total. Summers are hot and dry due to prevailing subtropical high-pressure systems. Rainfall is driven by mid-latitude cyclones and orographic effects from the nearby Pamir-Alay range. Winter snowfall is light and short-lived. This precipitation pattern is vital for agriculture and irrigation in the Zarafshan Valley, relying on seasonal rain and snowmelt (Figure 2).

2.2. Methodology

The present study aimed to identify suitable surface locations for rainwater harvesting and artificial groundwater recharge. This was achieved through the application of the AHP, following the methodological framework outlined by Estoque (2012) and Murayama (2012) [37][38]. The consistency ratio (CR) was calculated for each matrix to ensure the high consistency and reliability of the judgements. All CR values are below 0.8, confirming acceptable consistency.

2.3. Data Collection and Preprocessing

Various studies have been evaluated to finalize the parameters of AHP for semi-arid regions, such as Samarkand, Uzbekistan. Eight parameters were selected in identifying the most suitable locations for rainwater harvesting and artificial recharge (Table 1).

2.3.1. Geology

The analog geological map was geo-rectified and digitized to extract the study area. Various rock types influence recharge processes differently based on their inherent properties, such as permeability and porosity, which determine the rate and effectiveness of groundwater infiltration [26][39].

2.3.2. Soil Type

The lithological map was obtained and digitized

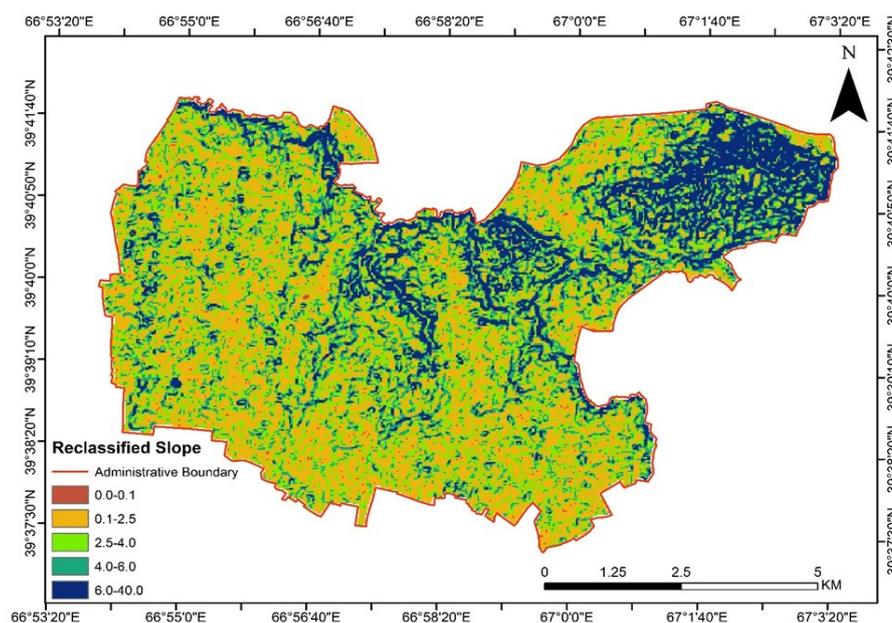


Figure 3. Reclassified slope map and its spatial distribution.

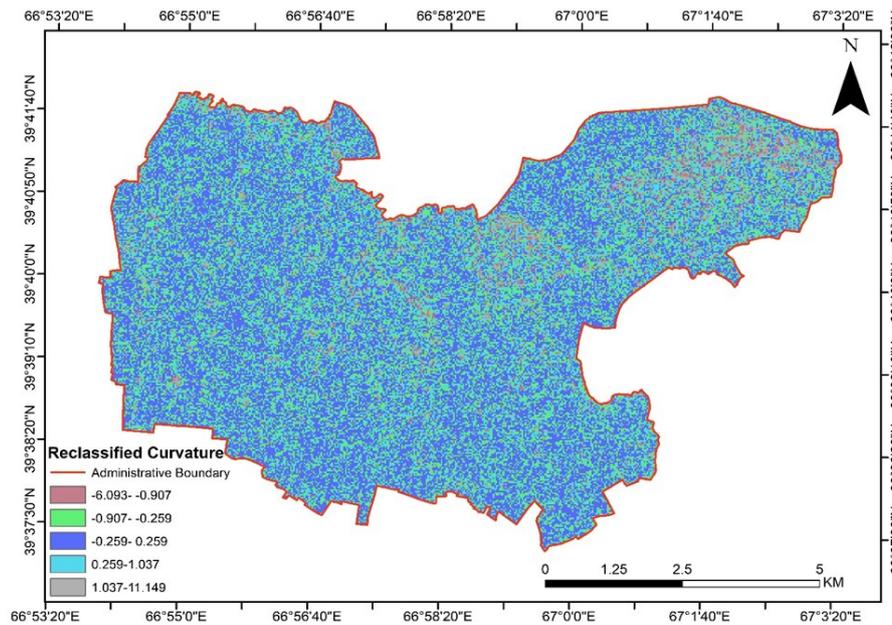


Figure 4. Reclassified map of curvature.

to prepare the soil map of the study area. Soil plays a critical role in the effectiveness of artificial groundwater recharge, influencing both the infiltration rate and the movement of water to deeper aquifers [24][40].

2.3.3. Land Use and Land Cover

The land use and land cover (LULC) significantly affects groundwater recharge by altering surface runoff, infiltration capacity, and evapotranspiration rates. Natural vegetation, such as forests and grasslands, typically promotes higher infiltration and recharge due to enhanced soil structure and reduced surface sealing. In contrast, urban areas with impervious surfaces (e.g., roads, buildings) limit infiltration and increase surface runoff, thereby reducing recharge potential. Agricultural practices can either enhance or hinder recharge depending on irrigation methods, soil compaction, and crop type [41][42].

2.3.4. Slope

The slope of a land surface significantly affects the rate and amount of water infiltration. On steeper slopes, gravitational forces increase the velocity of surface runoff, thereby reducing the time water remains in contact with the soil. This decreased contact time limits the amount of water infiltrating the ground [43]-[45].

2.3.5. Curvature

Slope curvature significantly affects water movement and infiltration, thereby influencing groundwater recharge. Concave slopes (positive curvature) tend to concentrate surface water flow into depressions, increasing water residence time and promoting greater infiltration and subsurface recharge [46][47]. In contrast, convex slopes (negative curvature) disperse surface water, accelerating runoff and reducing the opportunity for infiltration and groundwater replenishment [48].

2.3.6. Drainage Density

Drainage density influences the indicator for suitable artificial recharge locations by indirectly indicating the permeability and porosity of the terrain related to the surface runoff [44][49].

2.3.7. Lineaments

Lineaments indicate zones of faults, fractures, and joints, which significantly influence movement, accumulation, and recharge of groundwater [26][50][51]. Proper mapping and analysis of lineaments are crucial for effective groundwater resource management, especially in regions vulnerable to water scarcity.

2.3.8. Geomorphology

Groundwater recharge is a function not only of climatic factors like precipitation but also of surface

and subsurface characteristics, including the geomorphic setting [52]. Different landforms control the movement of water, affecting where and how much water infiltrates into the subsurface. Valleys and flood plain often serve as major recharge zones due to the accumulation of runoff and the presence of permeable sediments that favor infiltration [53] while in arid and semi-arid regions, gently sloping pediments formed at the base of hills can act as effective recharge zones where sheet wash and runoff water infiltrate [54].

Eight parameters were selected and compiled from various sources. Analog maps for geology, soil types, and geomorphology were obtained from the Uzbekistan Atlas and subsequently georeferenced to focus on the study area. However, the geomorphology map showed no significant variation across the region to calculate weightage & rankings and was therefore excluded from further analysis (Table 1). The ASTER Digital Elevation Model (DEM) and Landsat 9 OLI satellite data were acquired from the USGS Earth Explorer (<https://earthexplorer.usgs.gov/>) for drainage, lineaments, and land use and land cover analysis.

The collected data underwent several preprocessing steps: analog maps were georeferenced and digitized using on-screen methods; the resulting shape files and DEM data were projected into a GIS environment using the Universal Transverse Mercator coordinate system.

Various thematic layers were generated for the study area. Specifically, slope, curvature, drainage density, and distance from lineaments were derived from the DEM, whereas the geology and soil type base maps were prepared from the analog sources. In addition, the LULC map were produced using Landsat 9 OLI data.

2.4. Criteria Determination

ArcMap 10.8.2 was utilized to create, edit, and adapt the criteria layers for analysis. All vector layers were converted to raster format at a 30 × 30 m resolution to ensure compatibility with the ASTER DEM and Landsat datasets. This rasterization process was essential for standardizing the input layers for the AHP, which incorporated the following parameters: geology, soil type, land use/land cover, slope, curvature, drainage density, and distance from lineaments (Table 2).

2.5. Factors Standardization and Ranking

The ranking of parameters was determined based on two primary criteria. First, terrain-related parameters such as slope, curvature, lineaments, and drainage density were classified into five categories based on their quantitative values. Second, thematic layers such as geology, soil types, and LULC were classified according to their categorical types, as supported by established methodologies [53][56][57].

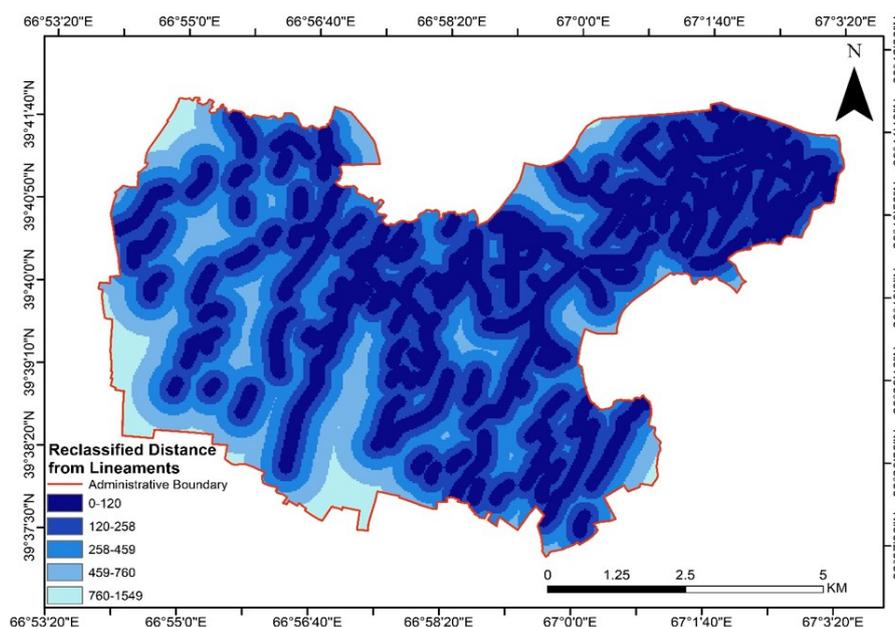


Figure 5. Reclassified map of distance from lineaments.

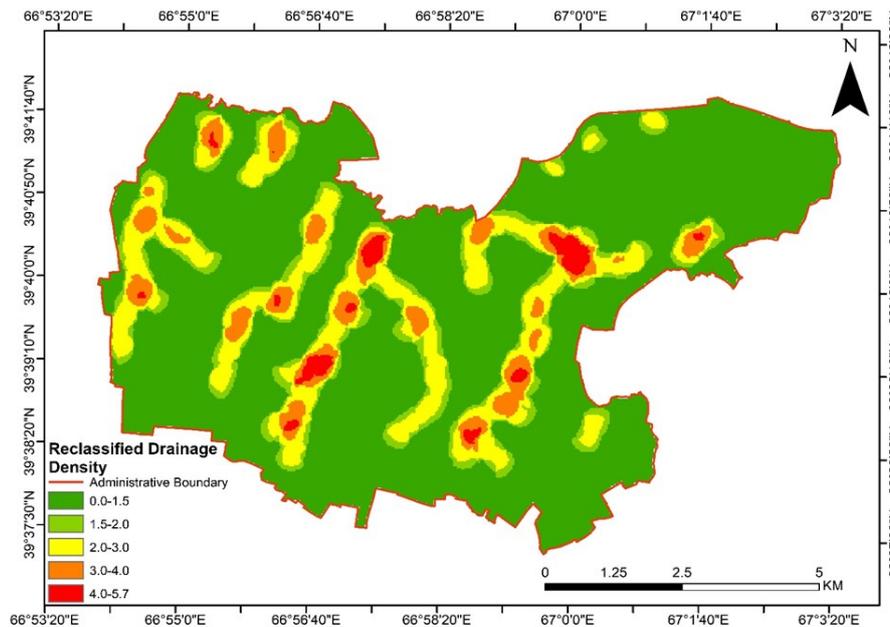


Figure 6. Reclassified map of drainage density.

2.5.1. Slope

Slope of the study area was calculated in degrees using advance thermal spaceborne reflection radiometer. Further, slope values were divided into five classes, reclassified on a scale from 1 to 5, and ranked accordingly (Figure 3). Lower slope values were assigned a rank of 1, indicating higher suitability for groundwater recharge, while higher slopes were given a rank of 5, representing lower suitability [27][34][58]-[63].

2.5.2. Curvature

Curvature values were initially divided into five classes based on manual classification and subsequently reclassified into five (Figure 4). These were then ranked from 1 to 5, where rankings were assigned based on the curvature's influence on runoff and infiltration potential [46][64]-[66].

2.5.3. Lineaments

Lineaments were extracted from the DEM and grouped into five proximity-based classes (Figure 5). These were reclassified and ranked from 1 to 5, with areas closer to lineaments assigned a rank of 1 due to their higher recharge potential, and distant areas assigned rank of 5 [27][34][58][60][61].

2.5.4. Drainage Density

Drainage density values were classified into five classes and ranked from 1 to 5 (Figure 6). Higher

drainage densities, indicative of reduced infiltration potential, were assigned higher ranks, while lower drainage density areas received lower ranks, reflecting greater suitability for groundwater recharge [27][34][49][60]-[62][67]. Three surface variables, viz., geology, soil types, and LULC, were ranked based on a literature review and their impact on groundwater recharge.

2.5.5. Geology

The geological and soil map of the study area was obtained from the Cadaster Department of the Government of Uzbekistan and used to extract geological information for analysis (Figure 7). Two primary lithological units were identified: unclassified metamorphic rocks and sandstone. Based on their hydrogeological characteristics, the unclassified metamorphic rocks were assigned a rank of 1, while sandstone was ranked 2 (Table 3). This ranking reflects the higher suitability of sandstone for groundwater recharge, as supported by several previous studies [27][58][59][62][67].

2.5.6. Soil Types

The Zarafshan River is the principal fluvial system in the region, responsible for depositing sediments and shaping the surrounding plains (Figure 8). The study area consists of two predominant soil types: alluvial and loess. Among these, alluvial soils exhibit superior infiltration

capacity compared to loess soils, making them more favorable for groundwater recharge [27][34][58][59][61][67]. Consequently, alluvial soils were assigned a higher rank than loess soils in the analysis.

2.5.7. Land Use and Land Cover

The LULC data were categorized into five classes (Figure 9) and assigned ranks from 1 to 5 based on their relative influence on groundwater recharge. Built-up areas received the lowest rank 1 due to their impervious surfaces, which significantly hinder infiltration [34][58][59][61][62].

2.6. Criteria Aggregation

The seven thematic raster layers were integrated in ArcMap using the weighted overlay analysis technique. Each layer was input into the weighted overlay tool, with standardized scale values and

influence levels assigned based on insights from previous studies. To ensure an unbiased evaluation, equal weights were allocated to all layers, indicating that each parameter was considered to contribute equally to the final groundwater recharge potential map.

2.7. Validation

Groundwater levels information was collected to validate the current research. It was observed that a significant decline in groundwater levels up to 5 m occurred in various regions of Uzbekistan, including Navoi, Samarkand, Jizzakh, Kashkadarya, Namangan, Fergana, and Andijan. This alarming drop is primarily attributed to the uncontrolled and unauthorized drilling of wells, which continues despite regulatory constraints.

In response to this growing crisis, the government of Uzbekistan has mandated the development of a comprehensive groundwater

Table 3. The selected parameters and their rank categorization.

Geology		Soil Types		Land Use and Land Cover	
Types	Ranks	Types	Ranks	Classes	Ranks
Unclassified Metamorphic Rocks	1	Alluvial Soil	1	Vacant Land	5
Sandstone	2	Loess Sand	2	Vegetation	2
				Water Bodies	4
				Built-up Area	1

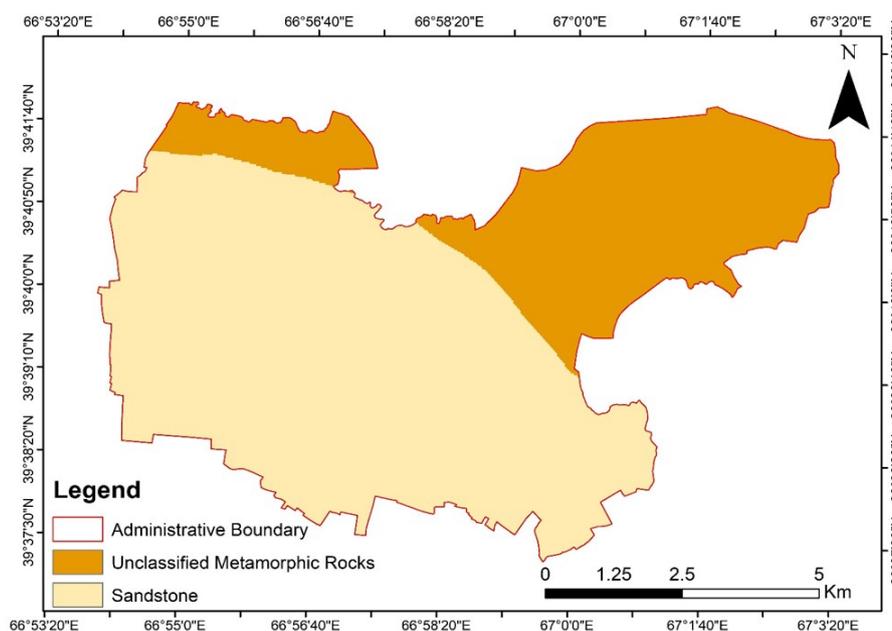


Figure 7. Geology map of the study area.

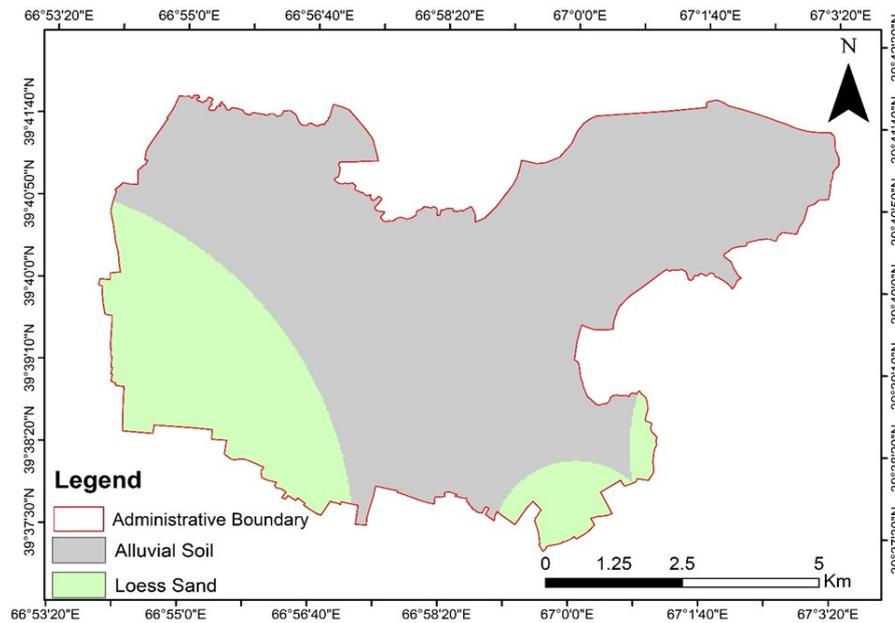


Figure 8. Soil map of the study area.

protection strategy. A key measure includes the imposition of a moratorium on both the drilling of new wells and the use of groundwater in areas where the water table has receded by more than 5 m. This regulation aims to prevent further degradation of aquifer systems and allow for partial natural recharge. A critical issue complicating groundwater governance is the lack of metering: currently, approximately 90% of wells are unmonitored, rendering it nearly impossible to accurately assess withdrawal volumes. To address this, all users of underground water are now legally required to equip their extraction points with water meters by January 1, 2024. To ensure data-driven management of the country's groundwater resources, geological exploration activities will be intensified. These surveys aim to re-evaluate and update the status of declining aquifers. Moreover, a significant institutional innovation is the creation of the State Geological Monitoring Service, which will be tasked with overseeing the state of groundwater reserves, integrating real-time monitoring technologies, and establishing a unified system for safeguarding against hazardous geological phenomena such as land subsidence, sinkholes, and contamination.

3. RESULTS AND DISCUSSIONS

The seven selected parameters were reclassified

into five suitability classes, spatially distributed across Samarkand City, to facilitate the identification of optimal zones for rainwater harvesting and artificial groundwater recharge (Figure 10). In this classification scheme, lower values represent areas with minimal suitability, while higher values indicate regions with optimal conditions for both surface water harvesting and subsurface recharge. The resulting suitability map was imported into the ArcGIS environment, where built-up areas—comprising urban centers and industrial zones—were excluded from the analysis. This exclusion was based on the well-documented negative impact of impervious surfaces, which dominate urban landscapes and significantly hinder natural infiltration processes. These surfaces increase surface runoff, reduce groundwater recharge, and contribute to urban flooding [27][34][58][59][61][67].

Despite these limitations, rainwater harvesting presents an effective strategy to mitigate such impacts by capturing runoff from impervious areas and redirecting it into artificial recharge systems, such as injection wells and recharge pits. Such systems enable the sustainable management of storm water while enhancing the recharge of underlying aquifers. However, field observations and available infrastructure data indicate that Samarkand currently lacks dedicated rainwater harvesting facilities. Although Uzbekistan's Law

“On Water and Water Use” (Law No. 733, 2021) recognizes rainwater harvesting and artificial recharge as important components of sustainable water resource management, implementation remains limited due to the absence of detailed regulatory guidelines, technical standards, and enforcement mechanisms at the local level. Moreover, institutional capacity, public awareness, and financial incentives necessary to support the development and maintenance of such infrastructure are currently insufficient. As a result, municipalities often lack the direction and resources needed to integrate rainwater harvesting into urban planning and water conservation strategies, hindering progress toward widespread adoption and long-term groundwater sustainability. The final suitability map highlights several zones across the city with high potential for rainwater harvesting and artificial recharge. Notably, the northwestern part of Samarkand emerged as particularly favorable, suggesting a strategic opportunity for the development of managed aquifer recharge infrastructure in this region. Such interventions could play a critical role in enhancing urban water resilience and addressing long-term water security challenges in the face of climate variability and urban expansion.

Land use and land cover analysis indicate that the expansion of impervious surfaces in Samarkand has substantially reduced natural infiltration,

thereby limiting groundwater recharge capacity. This spatial constraint also restricts opportunities for establishing effective recharge infrastructure. Concurrently, the city’s population has doubled over the past two decades, intensifying pressure on groundwater resources. Urban vegetation has also been significantly altered. Much of the natural vegetation cover has been replaced by artificially managed parks and roadside plantings, which often consist of non-native species with limited ecological or hydrological function [34][58][59][61][62]. These plantings contribute little to reducing evapotranspiration or enhancing local rainfall retention. Moreover, the absence of localized water treatment systems further exacerbates groundwater stress, as untreated wastewater and runoff are not effectively reused or redirected for recharge. The combined impact of over extraction, mismanagement, and inadequate urban planning poses a serious threat to the sustainability of aquifer resources, jeopardizing groundwater availability for future generations.

The current study utilized an AHP to evaluate the spatial suitability of Samarkand City for rainwater harvesting and artificial groundwater recharge. The analysis classified the urban landscape into four distinct categories: good, poor, not suitable and very poor. The "good" category encompasses areas exhibiting favorable conditions for water harvesting and aquifer recharge,

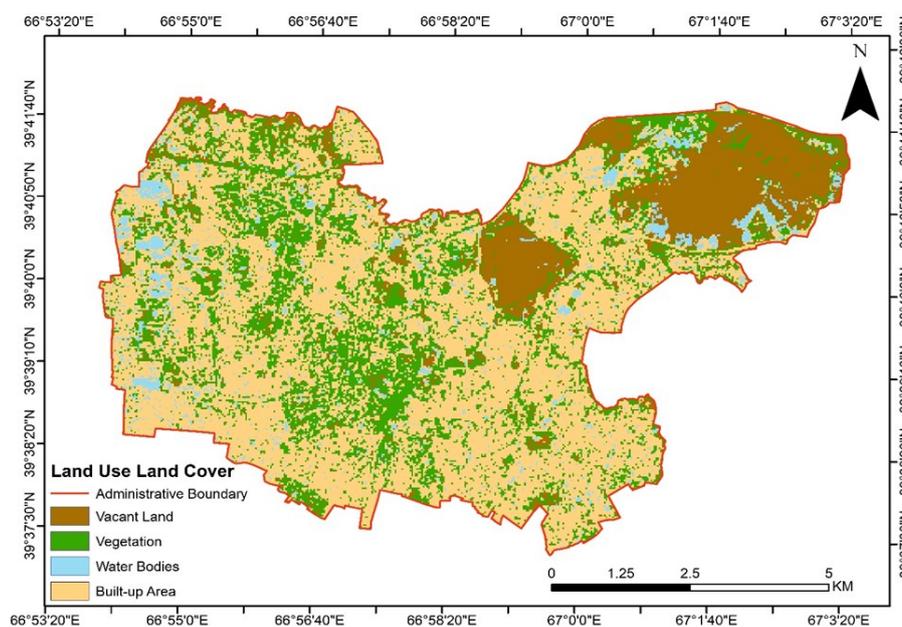


Figure 9. Land use and land cover map of the study area.

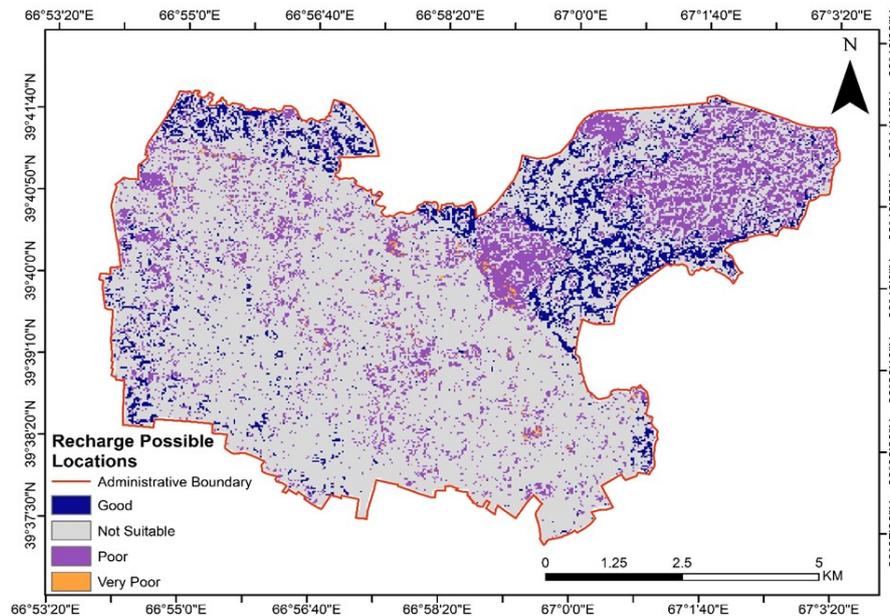


Figure 10. The optimal artificial groundwater recharge locations using AHP of the study area.

characterized by permeable soils, gentle slopes, suitable land use/land cover, and proximity to natural drainage or lineaments. These areas are strategically important for implementing recharge infrastructure such as recharge pits, infiltration trenches, and injection wells. In contrast, the "poor" category includes regions with limited recharge potential due to less favorable hydrogeological and surface conditions. While technically feasible, interventions in these areas may require additional engineering measures or incur higher costs. The "not suitable" and "very poor" categories represent zones where groundwater recharge is either extremely limited or entirely unfeasible. These typically correspond to dense urban settlements, industrial zones, steep slopes, or areas with highly impervious surfaces, which restrict infiltration and facilitate rapid surface runoff. This spatial classification not only guides the prioritization of recharge interventions but also supports urban planners and policymakers in identifying areas where land use modifications, policy interventions, or engineered solutions are necessary to enhance groundwater sustainability. The results underscore the importance of integrated urban water management and the need for strategic planning to counteract groundwater depletion in rapidly urbanizing environments such as Samarkand.

4. CONCLUSIONS

The optimal sites for rainwater harvesting and artificial groundwater recharge in Samarkand City were identified through the application of the AHP within a GIS framework. The results confirmed the effectiveness of the methodology in delineating potential recharge zones across the city, thereby contributing valuable insights for integrated groundwater management, aquifer rehabilitation, and long-term water level recovery. However, a key limitation of the study lies in its reliance on coarse-resolution analog datasets, which may introduce spatial inaccuracies and limit the precision of the findings. As such, this research should be regarded as a preliminary reconnaissance effort, providing a foundational assessment for guiding future, more detailed investigations. The use of high-resolution geological, soil, and geomorphological data is expected to significantly enhance the accuracy of recharge site identification. To build on these findings, it is recommended that future studies incorporate finer-scale satellite imagery and detailed utility infrastructure maps to refine site selection and assess feasibility at a more granular level. Furthermore, the Government of Uzbekistan is encouraged to integrate rainwater harvesting and artificial recharge strategies into future water-related legislation, making their implementation a

mandatory component of sustainable urban water management.

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Conflicts of Interest

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI

Not Applicable.

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