

GIS-Based Hydrogeomorphic Approach for Identification of Suitable Sites for Artificial Groundwater Recharge Structures in Gaya Ji City of Bihar, India

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Abstract: Groundwater is the principal source of domestic, agricultural and industrial water supply in the alluvial tracts of the Gangetic plain. The present study integrates remote sensing and Geographic Information System (GIS) based hydrogeomorphic analysis with field-based verification to identify suitable sites for artificial groundwater recharge structures in Gaya ji City in Gaya District, of Bihar. A Digital Elevation Model (DEM) derived from SRTM data (30 m resolution) was used to generate slope, flow direction, flow accumulation and drainage network layers in ArcGIS, while Survey of India toposheets (1:50,000; sheet nos. 72H1 and 72D13) and Google Earth Pro imagery (~5 m resolution) supported terrain verification through elevation-profile analysis. The integrated interpretation of these thematic layers, combined with the hydrogeological framework reported by the Central Ground Water Board (CGWB, 2022) for Gaya District, revealed that the study area is dominated by gentle slopes (0°-4.4°, locally up to 43.4° on isolated hillocks) and elevations ranging from about 97 m to 238 m above mean sea level, both of which favour infiltration over rapid runoff. Eight candidate locations were identified and evaluated against CGWB (2015) site-selection guidelines, of which recharge trenches were recommended at four sites associated with dispersed sheet-flow and gentle terrain and recharge pits at four sites with moderate, spatially limited runoff. An indicative cost-benefit assessment suggests recharge pits (₹20,000-₹40,000 per structure) and recharge trenches (₹40,000-₹80,000 per structure) are low-cost, low-maintenance interventions with an expected service life of 15-25 years. The study demonstrates that an integrated, low-cost GIS and field-verification workflow can provide a scientifically defensible first-order screening of artificial recharge sites in data-scarce urban settings of the Indo-Gangetic plain.

Keywords: Artificial groundwater recharge; GIS; Digital Elevation Model; slope analysis; drainage network

1. INTRODUCTION

Groundwater constitutes one of the most critical freshwater resources in India, supporting a large share of domestic, irrigation and industrial demand, particularly across the densely populated alluvial plains of the Ganga basin [1]. Rapid urbanisation, population growth and intensive agricultural withdrawal have led to a steady decline in groundwater levels in several parts of the country, prompting increased emphasis on managed and artificial recharge to sustain aquifer storage [2], [3]. Artificial groundwater recharge, defined broadly as the intentional augmentation of subsurface water storage through structures that intercept and infiltrate surface runoff, has therefore become a central component of groundwater management strategy in India, guided principally by the technical manual of the Central Ground Water Board [4].

The success of any artificial recharge programme depends critically on the correct identification of sites where terrain, slope and drainage conditions favour infiltration over rapid runoff loss [1], [2]. Over the past two decades, the integration of remote sensing and Geographic Information System (GIS) techniques with hydrogeological interpretation has emerged as the standard approach for recharge-site selection, since it allows terrain, drainage and morphometric parameters to be analysed synoptically over an entire catchment rather than through point observations alone. More recent work has formalized this into GIS-based multi-criteria decision analysis (GIS-MCDA), in which thematic layers such as slope, geology, soil, land use, drainage density and lineament density are individually scored and combined, typically using an Analytic Hierarchy Process (AHP) or a weighted-overlay procedure, into a composite recharge-suitability map. Reviews

of this literature confirm that slope, drainage density, and terrain morphology are consistently among the most influential parameters governing recharge suitability across diverse hydrogeological settings [1].

In many field-level and reconnaissance studies, however, a full multi-parameter GIS-MCDA exercise is not always feasible because of data limitations, particularly with respect to subsurface geology, soil permeability and land-use layers at fine spatial resolution [5], [6]. In such situations, an integrated terrain and drainage-based approach, using DEM-derived slope, flow direction and flow accumulation together with field verification, can still provide a scientifically grounded first-order assessment of recharge suitability, especially at the scale of an individual town or block [7], [8]. The present study adopts this approach for Gaya ji City in Gaya District, Bihar, an area situated within the Middle Gangetic alluvial plain where groundwater is intensively used and where the hydrogeological setting has been documented by the CGWB aquifer-mapping programme.

The specific objectives of the present study are: (i) to characterize the terrain, slope, and drainage conditions of Gaya City using SRTM DEM-derived thematic layers in a GIS environment; (ii) to identify and field-verify locations suitable for artificial groundwater recharge structures through elevation-profile analysis in Google Earth Pro and comparison with Survey of India toposheets; (iii) to recommend appropriate recharge structures (recharge pits versus recharge trenches) at each identified site in accordance with CGWB (2015) guidelines; and (iv) to provide an indicative cost-benefit assessment of the proposed structures to support planning and implementation.

2. STUDY AREA

The study area comprises Gaya City and its surroundings in Gaya District, southern Bihar, India, falling within Survey of India toposheet nos. 72H1 and 72D13 (scale 1:50,000). The area lies within the Middle Gangetic alluvial plain, a region whose regional hydrogeological framework, aquifer geometry, and groundwater occurrence have been documented in detail by the Central Ground Water Board under its National Aquifer Mapping (NAQUIM) programme, specifically in the report Aquifer Mapping and Management of Groundwater Resources, Gaya District, Bihar State (CGWB, 2022), which was used in the present study as the principal secondary reference for regional hydrogeological interpretation. The location of the study area is presented in Figure 1.

Analysis of the SRTM DEM shows that elevation within the study area ranges from approximately 97 m to 238 m above mean sea level, with comparatively higher terrain in the central-southern and northern parts of the study area and lower-lying plain tracts elsewhere. This elevation contrast, together with the predominance of gentle slopes, exerts a first-order control on surface runoff generation, drainage development, and the spatial distribution of zones favourable for infiltration and groundwater recharge, as detailed in the Results and Discussion.

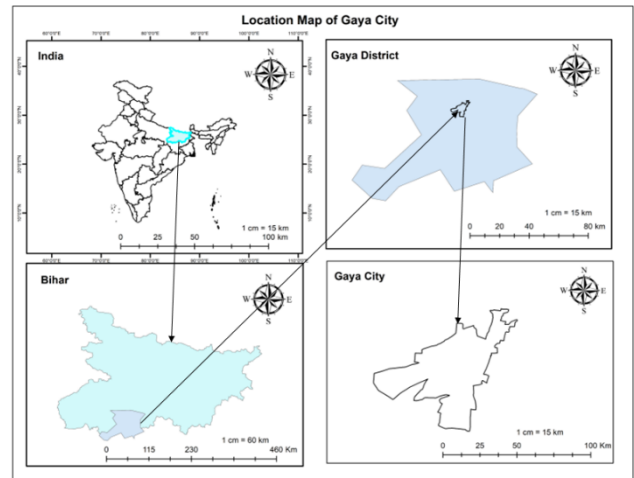


Figure 1. Location of the Study Area

3. MATERIALS AND METHODS

3.1 Datasets Used

The present study utilized the following spatial and hydrogeological datasets for terrain analysis, groundwater assessment, and artificial recharge site selection. All the essential information is given in Table 1.

Table 1. Description of Dataset

Dataset	Application
SRTM DEM (30 m resolution)	Terrain analysis; derivation of elevation, slope, flow direction, and flow accumulation layers in ArcGIS to understand runoff movement, drainage behavior, and infiltration-favorable zones.
Survey of India Toposheets (1:50,000; sheet nos. 72H1 and 72D13)	Reference maps for drainage characteristics, stream order, elevation features, and general topographic conditions; verification of drainage patterns identified through GIS analysis.
Google Earth Pro imagery (~5 m resolution)	Visual interpretation and site-level field verification; measurement and elevation-profile (path) tools used to assess local slope behaviour, upland-lowland relationships, and approximate surface-runoff movement at candidate recharge sites.
CGWB Report, Gaya District, Bihar (July 2022)	Secondary reference for regional hydrogeological conditions, aquifer characteristics, groundwater occurrence, and groundwater management practices, used to support interpretation of GIS-derived observations.

3.2 Methodology

3.2.1 Overall analytical framework

A sequential hydrogeomorphic-GIS workflow was adopted to identify candidate locations for artificial groundwater recharge. The procedure comprised (i) preparation and hydrological conditioning of the 30 m SRTM Digital Elevation Model (DEM); (ii) derivation of elevation and slope; (iii) extraction of D8 flow direction and flow accumulation; (iv) delineation and ordering of the drainage network; (v) preliminary screening of terrain and runoff-concentration conditions; (vi) site-level verification using Google Earth Pro elevation profiles and Survey of India

toposheets; and (vii) assignment of the appropriate recharge structure using the decision rules derived from CGWB guidance. The workflow was deliberately designed as a reconnaissance-level screening method rather than a weighted GIS-MCDA model because fine-resolution information on

soil permeability, subsurface lithology, depth to groundwater and land use/land cover was not available consistently for all candidate locations. All the steps are presented in Figure 2.

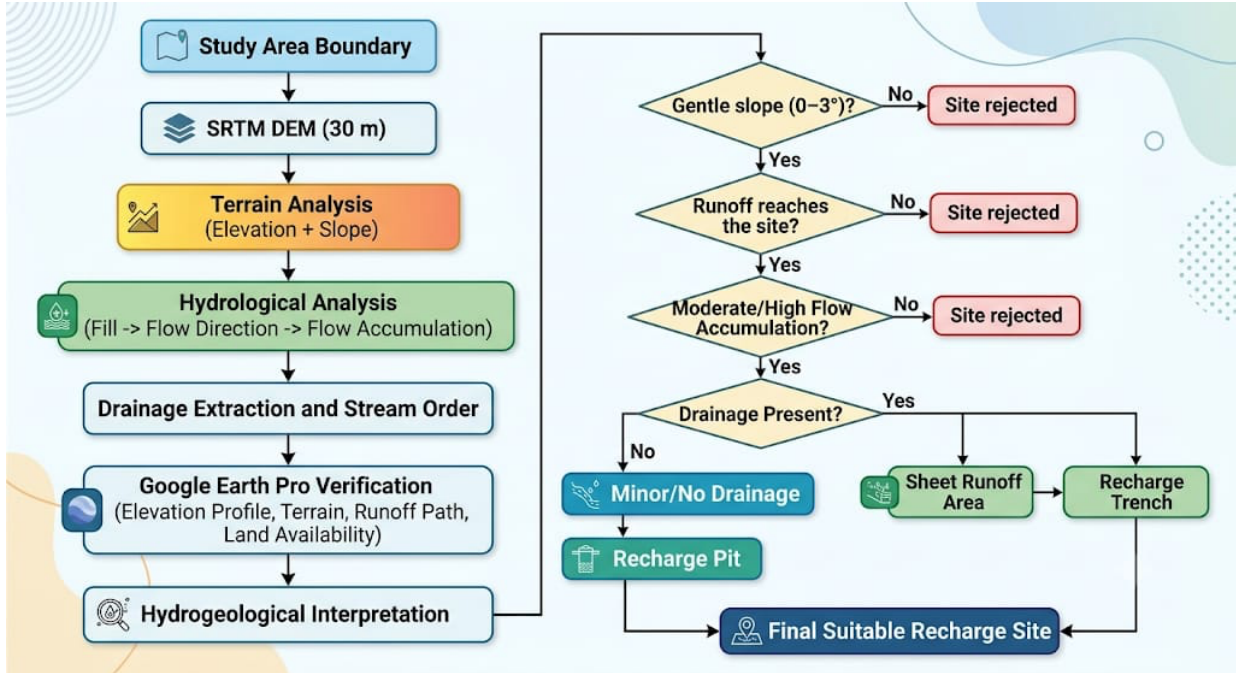


Figure 2. Methodology flowchart for the identification of suitable artificial recharge structure sites

3.2.2 DEM preparation and hydrological conditioning

The SRTM DEM (30 m spatial resolution) was clipped to the study-area boundary and inspected for sinks and anomalous elevation cells. A hydrologically conditioned or 'filled' DEM was then generated in ArcGIS before flow modelling. The fill operation was necessary because spurious depressions in a raster DEM can interrupt the downslope routing of water and produce artificial breaks in the derived drainage network. The resulting DEM provided the base surface from which slope, flow direction and flow accumulation were derived.

3.2.3 Slope estimation

Slope was calculated from the local elevation gradient of the DEM. For a raster cell, slope represents the maximum rate of change in elevation relative to horizontal distance and was expressed in degrees. Conceptually, the slope angle can be represented as equations 1.

$$S = \tan^{-1} \left(\sqrt{\left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2} \right) \quad (1)$$

where S is the slope angle (degrees), z is elevation, and x and y represent the horizontal coordinate directions. The derived slope surface was classified into the same suitability classes used in the Results section (0–3°, 3.1–7°, 7.1–11°, 11.1–18°, and 18.1–34°). These classes were interpreted in relation to

runoff velocity and infiltration opportunity, with lower slopes considered more favourable for recharge screening because they generally allow greater surface residence time.

3.2.4 Flow direction and flow accumulation

The hydrologically filled DEM was used to derive the flow-direction raster using the D8 approach available in ArcGIS. Under the D8 algorithm, each cell is assigned to the neighbouring cell with the greatest downslope gradient, thereby defining the principal direction of surface-water movement. The flow-direction surface was subsequently used to calculate flow accumulation, which represents the number of upstream cells draining through each cell equations 2.

$$F(i) = 1 + \sum F(j) \quad (2)$$

where F(i) is the flow-accumulation contribution at cell i and the summation represents contributing upstream cells j. In practical GIS terms, cells with low accumulation values were interpreted as runoff-source or local-divide areas, whereas progressively higher values represented sheet-flow convergence and established drainage pathways. The observed flow-accumulation range of 0–8944 was subsequently interpreted qualitatively to distinguish runoff-source, sheet-runoff, runoff-concentration and drainage-channel conditions.

3.2.5 Drainage-network extraction and stream ordering

The drainage network was extracted from the flow-accumulation raster using the hydrologic tools available in ArcGIS. The resulting drainage pathways were compared visually with the Survey of India topographic sheets to ensure that the GIS-derived network was consistent with mapped surface drainage. Stream order was assigned using the Strahler hierarchical concept: first-order streams are unbranched channels; two first-order streams combine to form a second-order stream; and two streams of the same order combine to produce the next higher order. The resulting first- to fourth-order drainage system was used as a qualitative indicator of runoff concentration and the scale of recharge intervention appropriate at a candidate location.

3.2.6 Hydrogeomorphic screening and candidate-site identification

Candidate sites were identified by overlaying and jointly interpreting the DEM, slope, flow-direction, flow-accumulation and drainage-network information. The screening logic followed three sequential conditions. First, terrain had to provide a relatively gentle surface suitable for temporary retention and infiltration. Second, a plausible runoff source or pathway had to be present, indicated by flow accumulation, sheet-flow convergence or proximity to a lower-order drainage line. Third, the terrain relationship had to permit practical interception of runoff without requiring a large channel-based structure. No numerical weights were assigned to these criteria; instead, the study retained a transparent rule-based screening procedure so that the final site recommendations could be traced directly to observable terrain and drainage characteristics equations 3.

$$R_i = f(S_i, F_i, D_i, T_i) \quad (3)$$

where R_i denotes the recharge-screening outcome for candidate site i ; S_i represents slope condition; F_i represents flow-accumulation/runoff condition; D_i represents drainage influence or stream order; and T_i represents the local topographic setting verified from elevation profiles. The function f is qualitative rather than a weighted numerical index in the present study.

3.2.7 Field and visual verification of candidate locations

Each shortlisted location was examined using Google Earth Pro path and elevation-profile tools to verify the local upland-to-lowland relationship, apparent slope behaviour and likely direction of surface-water movement. The visual interpretation was cross-checked against the Survey of India toposheets and the regional hydrogeological information reported by CGWB (2022). A site was retained when the GIS-derived terrain interpretation was consistent with the observed elevation profile and when a plausible runoff-collection setting was evident. This step was used as a screening-level verification and not as a substitute for a detailed topographic survey, infiltration test or hydrogeological investigation.

3.2.8 Selection of recharge-structure type

The type of artificial recharge structure was assigned after the candidate sites had passed the hydrogeomorphic screening. Recharge trenches were assigned to gently sloping locations influenced by broader, dispersed sheet flow, because their elongated geometry can intercept and temporarily store runoff over a larger infiltration surface. Recharge pits were assigned to locations where runoff was more spatially confined, drainage influence was limited or land availability favoured a localized intervention. Major channel-based structures such as check dams and percolation tanks were excluded where the candidate location lacked a suitable major drainage channel. This decision rule was applied consistently to the eight final sites reported in Table 7.

3.2.9 Planning-level cost and life-cycle assessment

The economic assessment was intentionally treated as indicative rather than as a project-level financial appraisal. Construction and annual maintenance ranges were compiled for the two recommended structure types, and expected service life was used to frame the long-term maintenance requirement. For a future detailed project report, the life-cycle cost of a structure can be expressed as equations 4.

$$LCC = C_0 + \sum_{t=1}^n \frac{M_t}{(1+r)^t} \quad (4)$$

where LCC is life-cycle cost, C_0 is initial construction cost, M_t is maintenance expenditure in year t , r is the selected discount rate, and n is the service life in years. Because the present study does not contain site-specific recharge-volume measurements, avoided-water-supply costs or groundwater-level response data, a formal benefit-cost ratio was not calculated. Accordingly, the cost ranges presented in Tables 8–10 should be interpreted as planning estimates rather than evidence of quantified economic returns.

3.2.10 Quality control, reproducibility and uncertainty

Quality control was maintained by using a common 30 m DEM as the source for all terrain-derived layers, hydrologically conditioning the DEM before flow modelling, cross-checking the extracted drainage network against Survey of India topographic information, and independently examining shortlisted locations with Google Earth Pro elevation profiles. The approach nevertheless remains subject to the vertical and horizontal limitations of the DEM, the scale of the source topographic maps, and the absence of site-specific subsurface and infiltration measurements. Therefore, the output should be interpreted as a first-order spatial screening of recharge opportunities; final engineering design and implementation require field survey, infiltration/percolation testing, groundwater-depth assessment and verification of site coordinates.

4. RESULTS AND DISCUSSION

4.1 Digital Elevation Model (DEM) Analysis

The DEM prepared from SRTM data (30 m resolution) shows considerable variation in elevation across the study area, ranging from approximately 97 m to 238 m above mean sea level (Figure 3), with higher elevation zones mainly in the central-southern and northern parts of the study area and relatively lower elevations in the surrounding plain regions. Since water naturally moves from higher to lower elevation under gravity, elevated zones function as runoff-generating areas, whereas lower-elevation zones act as runoff-accumulation areas in which infiltration and groundwater recharge are more likely to occur. This elevation pattern indicates favourable conditions for localized groundwater recharge in the low-lying portions of the study area, consistent with the decision framework summarized in Table 2.

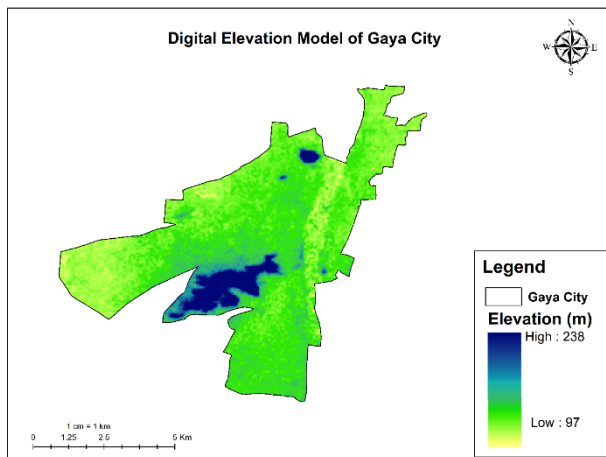


Figure 3. Digital Elevation Model of the study area

Table 2. Interpretation of DEM-based elevation zones for recharge site screening

Observation	Hydrogeological meaning	Decision
High elevation	Runoff-generating zone	Not selected for recharge structure
Low elevation	Runoff accumulation zone	Preferred for recharge investigation

4.2 Slope Analysis

Slope is among the most influential factors governing runoff generation, infiltration, soil erosion, and groundwater recharge (Sallwey et al., 2018). The slope map derived from the DEM shows that the study area is predominantly characterized by gentle slopes ranging from 0° to 4.4°, with moderate to steep slopes confined to isolated elevated terrain features and hillocks, where slope values reach up to 43.4° (Figure 4).

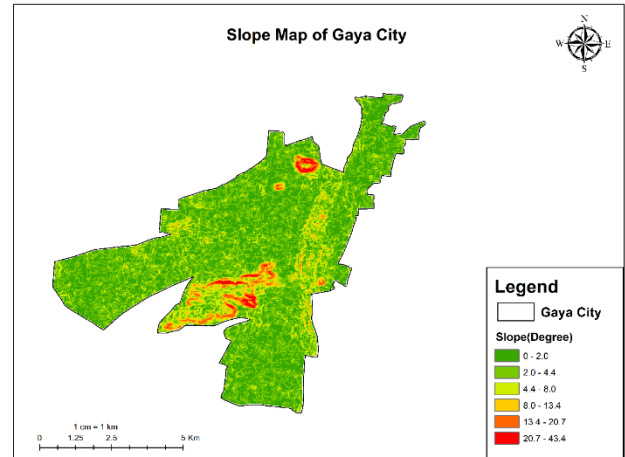


Figure 4. Slope map of the study area derived from the DEM

The dominance of gentle slopes reduces runoff velocity and increases the surface residence time of water, thereby favouring infiltration, whereas the steeper isolated zones facilitate rapid runoff and correspondingly lower recharge potential. The suitability classification adopted in the present study is summarized in Table 3.

Table 3. Slope Classification of Study area

Slope range (°)	Slope category	Terrain description	Runoff condition	Recharge suitability
0-3	Nearly level	Flat terrain	Very slow runoff	Very high
3.1-7	Gentle slope	Slightly sloping terrain	Slow runoff	High
7.1-11	Moderate slope	Undulating terrain	Moderate runoff	Moderate
11.1-18	Moderately steep	Rolling terrain	Fast runoff	Low
18.1-34	Steep slope	Hilly terrain	Very fast runoff	Very low

4.3 Flow Direction Analysis:

Flow direction analysis, carried out using the filled DEM, identifies the direction in which surface water from each raster cell moves toward its steepest downslope neighbouring cell (Figure 5). The analysis indicates that runoff movement is strongly controlled by local topographic gradients, with higher-elevation areas contributing runoff to adjacent lower elevations and forming a hydrologically connected drainage system. As the flow direction grid is a fundamental input for flow accumulation and drainage network delineation, this step is essential to subsequently identifying runoff-concentration zones and locating suitable

recharge structures, following the drainage-condition-based structure guidance summarized in Table 4.

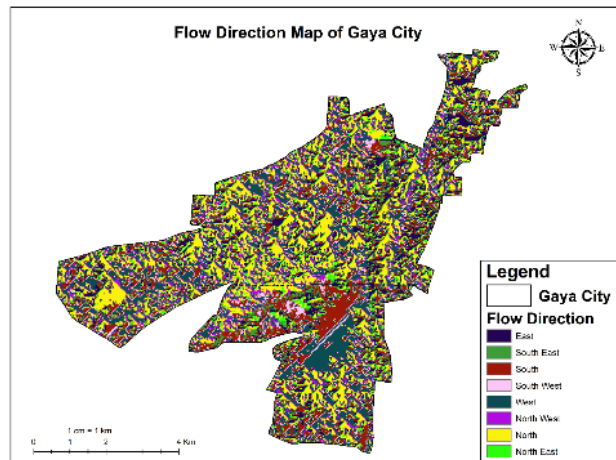


Figure 5. Flow direction map of the study area derived from dem

Table 4. Recommended structure type as a function of drainage condition

Drainage condition	Suitable structure
Major drainage	Check dam
Minor drainage	Recharge trench
No drainage	Recharge pit

4.4 Flow Accumulation Analysis

Flow accumulation analysis was performed to identify runoff-concentration zones and potential drainage pathways. Flow accumulation values in the study area range from 0 to 8944, indicating varying levels of upstream runoff contribution (Figure 6). Areas with high flow accumulation values represent locations where runoff from larger upstream catchments converges, generally corresponding to natural drainage pathways, whereas areas with low flow accumulation values are associated with elevated, runoff-generating terrain. The flow accumulation map confirms the presence of several runoff-concentration corridors within the study area, which are of particular relevance to recharge planning because they receive substantial runoff volumes during rainfall events; recharge structures positioned near these corridors can more effectively intercept runoff and

enhance infiltration, in line with the interpretive scheme in Table 5.

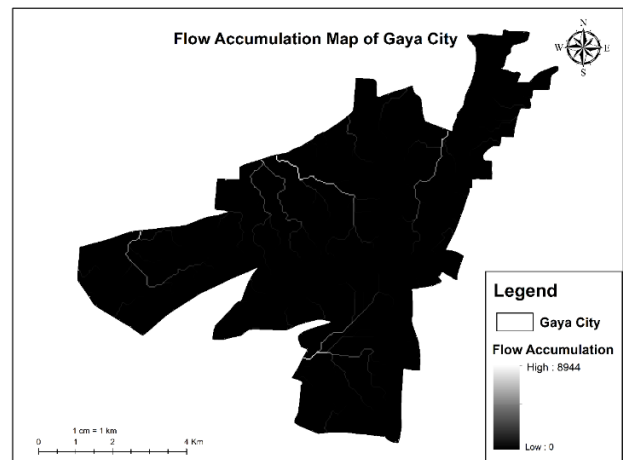


Figure 6. Flow accumulation map of the study area

Table 5. Interpretation of flow accumulation classes

Flow accumulation	Interpretation
Low	Runoff source area
Moderate	Sheet runoff
High	Runoff concentration
Very high	Drainage channel

4.5 Drainage Network Analysis

The drainage network, generated from the flow accumulation raster using ArcGIS hydrological tools, reveals a well-developed drainage system distributed throughout the study area (Figure 7). Stream-ordering analysis indicates the presence of first-, second-, third-, and fourth-order drainage channels, with the widely distributed lower-order streams contributing runoff to higher-order channels and forming an integrated network. The presence of multiple stream orders indicates active runoff transport and efficient surface-water movement, and the overall drainage pattern suggests moderate drainage development with adequate opportunity for runoff harvesting, particularly in areas adjacent to lower-order streams, which are considered suitable for small-scale recharge interventions capable of intercepting runoff before it exits the local catchment Table 6.

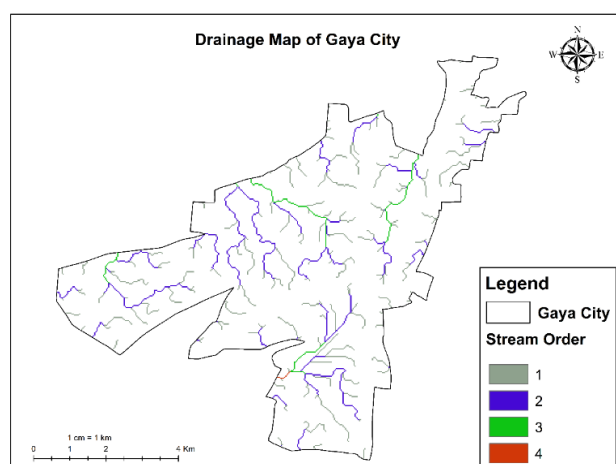


Figure 7. Drainage network of the study area extracted from the flow accumulation raster

Table 6. Recommended structure type as a function of stream order

Stream order	Recommended structure
1st order	Recharge pit, recharge trench
2nd order	Recharge trench, small check dam
3rd order and above	Check dam, percolation tank

4.6 Identification and Field Verification of Suitable Recharge Sites

The identification of suitable recharge sites was carried out through the integrated analysis of DEM, slope, flow direction, flow accumulation and drainage characteristics, together with field-level observations. The selected locations

are characterized by gentle slopes, favourable topographic conditions, and the presence of runoff pathways capable of supplying recharge water. Flow accumulation analysis identified runoff-concentration zones, slope analysis confirmed conditions favourable for infiltration, and the drainage network provided additional information on runoff movement and water availability during rainfall events. Field verification using Google Earth Pro elevation-profile and measurement tools further supported the selection of suitable recharge locations by confirming upland-lowland relationships and local terrain behaviour at each site figure 8.

Eight candidate sites were finalized through this integrated procedure. Their coordinates and the recommended structure at each location are summarized in Table 7 and presented in Figure 9.

Table 7. Location and recommended artificial recharge structure at the eight identified sites

S. No.	Latitude	Longitude	Recommended Structure
1	24°48'53.23"N	85°00'30.97"E	Recharge trench
2	24°49'01.02"N	85°00'47.25"E	Recharge trench
3	24°48'40.33"N	85°00'50.94"E	Recharge trench
4	24°46'57.21"N	84°59'58.29"E	Recharge pit
5	24°46'38.36"N	85°00'04.70"E	Recharge trench
6	24°46'08.11"N	85°00'02.93"E	Recharge pit
7	24°45'35.64"N	84°59'28.67"E	Recharge pit
8	24°46'8.83"N	84°56'37.85"E	Recharge pit



Figure 8. (a-h) Representative elevation-profile analysis at a candidate recharge site using Google Earth Pro path/measurement tool

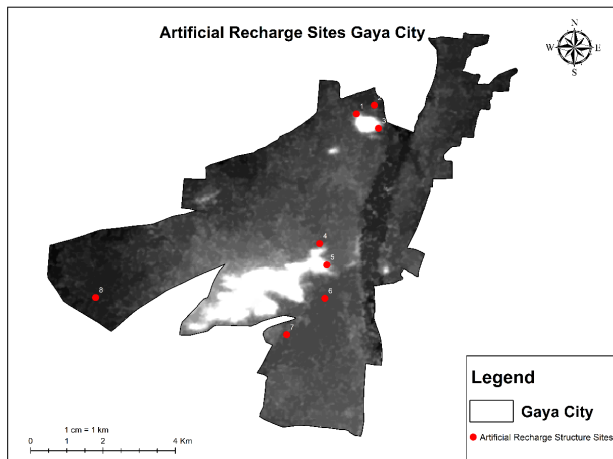


Figure 9. Location map of the eight proposed artificial recharge structure sites, Gaya City

4.7 Proposed Artificial Recharge Structures

Based on the hydrogeomorphic characteristics of the study area and the guidelines provided by CGWB (2015), recharge pits and recharge trenches were identified as the most suitable artificial recharge structures for the study area; large-scale, channel-based structures such as check dams were not considered appropriate at any of the selected sites because of the absence of major drainage-channel influence and the localized, sheet-flow nature of runoff generation there [14], [15].

■ Recharge Pit.

Recharge pits are recommended at locations where runoff availability is moderate, land availability is limited, and recharge is required at a localized scale (Sites 4, 6, 7, and 8 in Table 7). These structures facilitate downward movement of water through a filter-media system of sand, gravel, and boulders and are particularly effective where gentle slope conditions promote temporary ponding and infiltration of relatively small, concentrated runoff volumes [16].

■ Recharge Trench.

Recharge trenches are recommended at sites characterized by gentle slopes and broader, dispersed runoff-collection areas (Sites 1, 2, 3, and 5 in Table 7). Their elongated geometry provides a larger infiltration surface than recharge pits and is effective in intercepting sheet runoff generated during rainfall events, allowing water to spread over a greater area and thereby increasing recharge efficiency [17].

4.8 Indicative Cost-Benefit Assessment

An indicative, planning-level cost-benefit assessment of the proposed structures was carried out based on prevailing construction practices in India (Tables 8-10). The actual construction cost at each site should be finalized during the detailed project report (DPR) stage using the applicable state Schedule of Rates (SOR).

Both structures represent technically feasible and economically low-cost artificial recharge measures. Annual maintenance costs are modest relative to construction cost, and

regular pre-monsoon desilting and filter-media cleaning are essential to sustain infiltration efficiency and achieve the expected service life over the long term.

Table 8. Approximate construction cost of proposed recharge structures

Structure	Approx. construction cost (₹/structure)	Remarks
Recharge pit	₹20,000 - ₹40,000	Includes excavation, filter media (sand, gravel, boulders), PVC pipe (if required), labor, and finishing.
Recharge trench	₹40,000 - ₹80,000	Includes excavation, filter media, inlet arrangement, labor, and site restoration; cost varies mainly with trench length and width.

Table 9. Approximate annual maintenance cost of proposed recharge structures

Structure	Annual maintenance cost (₹/year)	Maintenance activities
Recharge pit	₹1,000 - ₹3,000	Desilting, cleaning of filter media, weed removal, pre-monsoon inspection.
Recharge trench	₹2,000 - ₹5,000	Desilting, vegetation removal, cleaning of inlet, repair of eroded sections.

Table 10. Expected service life of proposed recharge structures

Structure	Expected service life
Recharge pit	15-20 years
Recharge trench	20-25 years

4.9 Groundwater Management Implications

The integrated hydrogeomorphic analysis indicates that Gaya City possesses generally favourable conditions for artificial groundwater recharge. The predominance of gentle slopes, the presence of well-developed but locally minor drainage pathways and identifiable runoff-concentration

zones together create opportunities for enhancing groundwater resources through low-cost artificial recharge measures [18]. Implementation of the proposed recharge pits and recharge trenches is expected to reduce runoff losses, increase infiltration, improve groundwater storage, and support long-term groundwater sustainability by supplementing natural recharge during rainfall events, consistent with the CGWB (2022) characterization of the district's hydrogeological setting [19].

4.10 Comparison with GIS-Based Multi-Criteria

Recharge-Suitability Studies

The terrain-and-drainage based screening approach adopted in this study is broadly consistent with the wider body of GIS-based recharge-site-selection literature, in which slope, drainage density, and topographic parameters are repeatedly identified among the most influential controls on recharge suitability [19]-[21]. Most published studies, however, formalize site selection through a multi-criteria decision analysis (GIS-MCDA) framework in which several independently weighted thematic layers - typically including geology, soil texture, land use/land cover, depth to water table, and drainage/lineament density in addition to slope - are combined through an Analytic Hierarchy Process (AHP) or weighted-overlay procedure to generate a composite suitability index [18], [22]-[24]. The present study differs from this fuller GIS-MCDA framework in two respects: first, it relies on a smaller set of terrain-derived layers (DEM, slope, flow direction, flow accumulation, and drainage) supplemented by field-based elevation-profile verification rather than subsurface geological or pedological data; and second, sites were screened qualitatively against CGWB (2015) decision rules (Tables 2, 4, and 6) rather than through a formally weighted composite index.

This more limited approach is appropriate for a reconnaissance-level, town-scale assessment where subsurface lithological and soil-permeability data are not readily available and it has the advantage of remaining transparent and reproducible with minimal data requirements. Nevertheless, the absence of an explicit weighting scheme means that the relative importance of slope versus drainage versus flow accumulation in the final site ranking cannot be quantified and the study does not incorporate independent validation (for example, against observed pre- and post-monsoon water-level fluctuation data) of the kind used in several GIS-MCDA studies to test suitability maps against actual recharge response. These points are discussed further as limitations in Section 4.11.

4.11 Limitations of the Study

Several limitations should be noted in interpreting the results of this study. First, the analysis relies on a 30 m resolution SRTM DEM, which, while adequate for identifying broad terrain and slope trends, cannot resolve fine-scale micro-topographic features that may influence infiltration at the scale of an individual structure; site-specific topographic survey is recommended before final structure design. Second,

the site-selection procedure in this study is based principally on terrain, slope, and drainage parameters and does not incorporate subsurface geology, soil texture/permeability, depth to water table, or land-use data, all of which are recognized as important criteria in comprehensive GIS-MCDA based recharge-suitability studies (Sallwey et al., 2018). Third, the recommended structure type at each site (Table 7) was assigned through qualitative interpretation against CGWB (2015) decision rules rather than a formally weighted multi-criteria index, and no independent field or hydrological validation (e.g., pre- and post-monsoon water-level monitoring, infiltration testing) has yet been carried out to confirm the recharge performance of the recommended structures. Fourth, as noted in Section 4.6, the coordinate data available for Site 8 (Table 7) contained an evident transcription error in which the longitude field duplicated the latitude value; this has been flagged rather than corrected by assumption, and verification against the original field/GIS record is recommended before implementation. Future work should therefore aim to incorporate additional thematic layers, a formal AHP or weighted-overlay suitability index, and post-construction monitoring to validate and refine the site recommendations presented here.

4. CONCLUSION

The integrated assessment of DEM, slope, flow direction, flow accumulation, and drainage characteristics, supported by field verification using Google Earth Pro and reference to CGWB (2022) hydrogeological information, indicates that Gaya City possesses favourable conditions for artificial groundwater recharge. Gentle slope conditions (predominantly 0°-4.4°), localized runoff generation, and identifiable though minor drainage influence were found to support the implementation of recharge pits and recharge trenches at eight identified sites, in accordance with CGWB (2015) guidelines. No site was found to warrant a large channel-based structure such as a check dam. An indicative cost-benefit assessment suggests that the proposed structures are low-cost (₹20,000-₹80,000 per structure), require modest annual maintenance (₹1,000-₹5,000 per year), and have an expected service life of 15-25 years, making them technically feasible and economically viable interventions for local groundwater management.

While the terrain-and-drainage based approach adopted here provides a scientifically grounded, low-data-requirement screening method appropriate for reconnaissance-level planning, it should be complemented in subsequent work by additional thematic layers (geology, soil, land use, water-table depth), a formally weighted GIS-MCDA suitability index, and post-implementation hydrological monitoring, in order to validate and refine site selection and to support the broader goal of sustainable groundwater resource management in Gaya City and comparable urban settings of the Middle Gangetic plain.

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