Geological Influences on Watershed Hydrology and Command-Area Water Management: Comprehensive Review

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Abstract
The hydrology of watersheds is a basic function of their geological features, and these features heavily affect the functioning of irrigated command areas. This review collates the latest scientific research to provide an overview of the control of lithology, geomorphology, bedrock permeability, fractures, aquifer properties, drainage characteristics and geological heterogeneity on infiltration, groundwater recharge, runoff generation, baseflow and surface water-groundwater interactions. It also looks at how GIS, remote sensing, AHP, MCDA, hydrochemical analysis, tracer techniques and groundwater-flow modelling can help in evaluating recharge zones, groundwater potential and sub-surface connectivity. This review also examines the impact of these hydrogeological controls on seepage of canals, irrigation reliability, groundwater withdrawal, waterlogging, salinity, crop water needs, and conjunctive water use. Results show that for sustainable command area management, integrating the knowledge of the watershed geology with efficient irrigation practice, drainage planning, recharge enhancement, groundwater control, crop diversification and climate responsive options are essential. The study underscores the importance of field validation, aquifer-scale monitoring and spatially explicit decision-support tools to better manage ground water-use, lessen groundwater stress, and enhance long-term water use systems resilience at watershed and command-area scales. This integration can help maintain the reliability of water allocation, sustain landscape functionality and ensure agricultural productivity is matched to the hydrological capacity of landscapes.

Keywords: Watershed hydrology; Hydrogeology; Groundwater recharge; Command-area management; Geospatial assessment.

1. Introduction

The interaction of climatic conditions, topography, soil properties, land cover, drainage characteristics and subsurface geological structure all control the watershed hydrology. Geology plays a unique role among these factors in that it dictates the ability of the subsurface to store, transmit and release water. All of these factors, such as lithology, bedrock permeability, fracture networks, weathered zones and aquifer architecture, control infiltration, groundwater recharge, baseflow generation and interactions between surface and subsurface water systems. Therefore, the hydrological reaction of a catchment is not always determined by the surface topography or drainage pattern of the catchment. In the mountainous headwater catchment environment, Asano et al. (2020) showed that bedrock infiltration via subsurface flow pathways can greatly influence stream discharge, thereby suggesting that the extent of topographic catchments may not be representative of the nature of flow pathways. This underscores the importance of using geological information at the watershed scale for hydrological interpretation.

Groundwater contributions from forested and headwater catchments can be significantly different in various geological situations and the role of bedrock and subsurface connectivity is particularly important. Iwasaki et al. (2021) demonstrated that geology influences catchment size–groundwater contribution relationships, indicating that the flow regime for watersheds of comparable size could be different as a result of variations in the subsurface hydrology and structure. Likewise, Masaoka et al. (2021) showed that bedrock groundwater catchment areas can be used to gain valuable information about rainfall-runoff processes. They concluded that the movement of groundwater need not be controlled by surface watersheds and that also the spatial distribution of water in a watershed may be changed by subsurface flow. These processes have a direct impact on the magnitude, timing and persistence of runoff, and affect the baseflow in dry periods.

Another important mechanism of how geology affects watershed hydrology is through the interaction of groundwater and surface water. Water exchange between streams and aquifers can be directed and characterized in terms of both streambed permeability, aquifer properties, and geographic variability. Streambed and aquifer properties have been shown to play a key role in controlling exchange fluxes between groundwater and surface water, as noted by Tripathi et al., 2021. These interactions are especially significant for sustaining streamflow, groundwater recharge and availability of water during a given season. Heterogeneous geologic settings can result in very localized gaining and losing stream conditions, making watershed management and water-resource planning more difficult.

The geology also affects groundwater occurrence, recharge potential and hydrochemical properties. Gayathri et al. (2021) found that the groundwater chemistry varies significantly in space and time in the studied catchment area that contains both a complex geological gradient and a climatic gradient. This variation shows the strong dependence of the flow of ground water, reaction with rocks, recharge and local geology. These relationships can be vital to the understanding of groundwater quantity, as well as the suitability of groundwater for irrigation and other purposes. Groundwater availability, likely recharge areas and potential groundwater quality modifications due to geology are therefore important considerations with respect to hydrogeological characterization.

The use of remote sensing, geographic information systems (GIS) and multi-criteria decision making (MCDM) has also further improved the capacity to assess groundwater at watershed scales.Groundwater assessments at watershed scales have also been supported by the increasing use of remote sensing, geographic information systems (GIS) and multi-criteria decision making (MCDM) techniques. Abijith et al., (2020) employed multi-criteria analysis based on geographic information system to prioritize the groundwater recharge potential in Ponnaniyaru watershed in Tamil Nadu by considering geology, geomorphology, drainage, slope, soil and land use characteristics. Similarly, Rajesh et al. (2021) used the analytical hierarchy process to demarcate groundwater-potential zones in the Godavari River basin, proving the benefits of combining the various hydrogeological parameters for a spatial groundwater assessment. Saravanan et al. (2021) also demonstrated the applicability of remote sensing and GIS for delineation of groundwater-potential areas in the Arkavathi sub-watershed, Karnataka. These studies together prove that geospatial tools can be successfully developed to be effective decision support tools based on geological and hydrological data.

Geological controls assume even more importance in irrigated command areas, when natural hydrological processes are modified by the introduction of irrigating canals, pumping groundwater, withdrawing water for agriculture, and return flows. Intensive irrigation can affect groundwater levels, the recharge pattern, and the interaction between groundwater and surface water resources, necessitating integration of groundwater and surface water resources. Das et al. (2020) pointed out the sustainability issues in groundwater management in the Lower Ganga River basin, especially in the context of the changing climate in the area. Their results emphasize the importance of managing both water withdrawals and aquifer recharge and groundwater resources over time.

Therefore, a sound understanding of the geologic framework that controls infiltration, recharge, subsurface storage and groundwater movement is essential to effective water management in a command area. The present review therefore considers the effect of geological features on watershed hydrology and their implications in managing the water resources in the command area. Special focus is paid to bedrock infiltration, groundwater contribution, rainfall-runoff processes, interaction of groundwater to surface water, recharge potential, hydrochemical variability and hydrospatial groundwater assessment. Themes were also organized into a single unit in order to offer a holistic view of the contribution that geological knowledge can offer to more sustainable, efficient and spatial management of watershed and irrigation water resources.

2. Methodology

2.1 Review Framework

A structured review framework was adopted to examine how geological characteristics influence watershed hydrology and command-area water management. The review integrated evidence from hydrogeology, watershed science, groundwater dynamics, irrigation hydrology, remote sensing, and agricultural water management. Particular attention was given to lithology, bedrock permeability, fracture systems, aquifer properties, groundwater recharge, runoff generation, baseflow, groundwater–surface water exchange, and irrigation-water availability.

2.2 Literature Search Strategy

Relevant peer-reviewed literature was retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Search terms were combined using Boolean operators to improve thematic coverage and relevance. Major keywords included "watershed geology," "geological controls on hydrology," "bedrock infiltration," "groundwater recharge," "groundwater–surface water interaction," "aquifer characteristics," "rainfall–runoff processes," "groundwater potential," "command-area irrigation," "canal irrigation," and "agricultural water management." Related terms concerning geomorphology, hydrogeology, fracture networks, and geospatial groundwater assessment were also included.

2.3 Study Selection

Studies were included when they presented empirical, modelling, geospatial, or synthesis-based evidence linking geological conditions with watershed hydrological processes or irrigation and groundwater management. Priority was given to peer-reviewed studies with clearly described methods, measurable hydrological variables, and interpretable geological information. Studies were excluded when geological controls were treated superficially, hydrological processes were not directly assessed, or irrigation management was discussed without connection to watershed or groundwater dynamics. Duplicate records, non-scholarly material, short abstracts, and studies lacking adequate methodological detail were also excluded.

2.4 Data Extraction and Thematic Classification

Key information was extracted from each eligible study, including geological setting, watershed characteristics, hydrological variables, analytical methods, major findings, and management implications. The evidence was organized into thematic domains covering bedrock and lithological controls, groundwater recharge and storage, rainfall–runoff response, groundwater–surface water connectivity, groundwater-potential assessment, hydrochemical variability, geospatial applications, and command-area water management. This thematic structure enabled comparison across different watershed types and geological environments.

2.5 Evidence Synthesis and Critical Evaluation

A qualitative comparative synthesis was applied because the selected studies differed in geological setting, spatial scale, hydrological variables, datasets, and analytical techniques. Findings from hard-rock, alluvial, mountainous, forested, and irrigated systems were compared to identify consistent relationships, contrasting responses, and context-dependent controls. Greater interpretative weight was assigned to studies supported by field observations, validated hydrological modelling, hydrochemical evidence, or integrated geospatial analysis.

2.6 Research Gaps and Management Implications

The synthesized evidence was critically evaluated to identify unresolved scientific questions and methodological limitations. Particular attention was given to uncertainties related to subsurface connectivity, geological heterogeneity, recharge estimation, canal–aquifer interactions, and the transferability of watershed-scale findings to irrigation command areas. The final synthesis linked these gaps with priorities for recharge planning, sustainable groundwater abstraction, irrigation efficiency, and spatially informed water-resource management. It also highlighted priorities for integrated watershed–command management frameworks.

3. Geological Controls on Watershed Hydrological Processes

Geology is the physical backdrop on which watershed hydrology evolves, which dictates the partitioning of precipitation into infiltration, surface runoff, subsurface storage, groundwater recharge and delayed streamflow. Capacity of a landscape to receive, transmit and retain water depends on lithology, geomorphology, depth of weathering, fracture density, aquifer architecture, slope and drainage organization. These attributes are variable across a watershed and, for similar rainfall inputs, watersheds tend to have areas of varying response (hydrological response zones). Finally, spatial variations in recharge, runoff generation, groundwater availability and success of water-management interventions can only be interpreted with the geological data.

Lithology has a first order control by determining primary and secondary porosity, permeability and storage. Groundwater is commonly found in fractured and weathered areas in hard rock areas, and in unconsolidated and alluvial rocks, there is typically more intergranular storage and hydraulic continuity. Sutradhar et al. (2021) showed that lithology, geomorphology, drainage density, slope, soil and land-use properties are the most important factors that determine groundwater potential in a study area, and that no one of these properties explains the groundwater potential alone. The use of MIF and AHP models shows an application of the combination of geological and terrain elements to determine zones of different groundwater prospects. Where productivity of aquifers is greatly localized, such spatial differentiation is particularly significant.

Geomorphology plays a modifying role to these geological controls by influencing convergence of flow, residence time, infiltration opportunity, and spatial distribution of recharge. Water holding and percolation abilities vary widely between Valleys, Pediments, Floodplains, Weathered Uplands and Structural Depressions. Sahu et al. (2022) demonstrated that geospatial analysis in conjunction with AHP could delineate potential zones for recharge of groundwater and help to site appropriate structures for recharge. They found that infiltration tends to be better for gentle slopes, favorable geomorphic units, permeable terrain, and lower drainage density, while high drainage density and steep, heavily dissected terrain tend to favour rapid runoff. Thus the hydrological expression of geology is always related to the topographic and geomorphic expression of the landscape.

Another example of this interaction of geological and hydrological inputs is groundwater recharge. Sajil Kumar et al. (2021) noted that the estimation of recharge and water-balance assessment are still complex, as recharge is also dependent on soil hydraulic properties, vadose-zone thickness, aquifer characteristics, fracture connectivity and antecedent moisture conditions. They regulate the percentage of precipitation that infiltrates to the saturated zone and the rate of infiltration. Local variations in slope and sub surface properties can create significant spatial variability in recharge in mountain watersheds. This variation was shown by Rani et al. (2022) in the Upper Kosi watershed where the recharge potential and sensitivity of the watersheds varied depending on the groundwater enhancing strategies applied. Their findings confirm the requirement for site-specific recharge planning in consideration of the hydrogeological suitability of the site. The geological and hydrogeological characteristics have direct influences on infiltration and recharge, runoff behaviour, groundwater storage and the effectiveness of the water management in the command area, as summarized in Table 1.

Table 1. Geological and Hydrogeological Controls on Watershed Hydrology and Their Implications for Command-Area Water Management

Geological Factor	Hydrological Influence	Management Relevance
Lithology	Controls infiltration and storage	Identifies groundwater potential
Fractures and Weathering	Enhance subsurface flow	Guide recharge and aquifer

		development
Geomorphology	Regulates runoff and recharge	Supports watershed zoning
Slope	Influences runoff velocity and infiltration	Helps locate recharge structures
Drainage Density	Controls runoff concentration	Indicates recharge suitability
Aquifer Properties	Govern storage and transmissivity	Affect irrigation reliability
Vadose Zone	Regulates percolation to groundwater	Influences recharge efficiency
Canal–Aquifer Interaction	Alters groundwater recharge and levels	Supports conjunctive water management
Geological Heterogeneity	Creates spatial hydrological variability	Requires site-specific management

Geology also affects water balances in command areas where water is distributed from wells, canal seepage or return flows alter water balances. The effect of canal systems on aquifer recharge is variable, depending upon the permeability and storage properties of the underlying rocks and soils. Amarasinghe et al. (2021) demonstrated the close linkage between the performance of canal irrigation, water distribution, system efficiency and local water availability. Their analysis points out the need to consider the performance of irrigation, rather than just as a canal conveyance system.

Combined these studies demonstrate that watershed hydrology is a product of the geological structure, landform configuration, and water-management practices. Storage and transmissivity rely on lithology and weathering, spatial organisation of runoff and recharge depends on geomorphology, preferential pathways of subsurface flow depend on fractures and aquifer properties affect groundwater flow persistence. These controls also influence the management of artificial recharge, canal irrigation and groundwater abstraction. Therefore, a geology-informed watershed perspective is essential for the identification of recharge prone areas, placement of augmentation facilities, groundwater potential and understanding changes in irrigation reliability. The addition of geological, geomorphological and hydrological data gives a better foundation for sustainable watershed planning since the natural controls on recharge are tied to water use decisions, including enhancement of recharge and allocation of water in the command area. This holistic interpretation is especially useful when there are variations in recharge efficiency, groundwater persistence, and surface-water availability during the seasons due to climatic variability in a geologically diverse area.

4. Groundwater Recharge, Storage, and Surface Water–Groundwater Interactions

Groundwater recharge and storage are important aspects of watershed hydrology that affect many aspects of aquifer recharge, baseflow persistence, low flows, and seasonal availability of groundwater. They are subject to the control of the geological structure, the aquifer properties, terrain characteristics, drainage organization and rainfall dynamics, and their magnitude and distribution depend on these factors. Recharge is seldom evenly distributed in geologically diverse watersheds. Rather, it is focused on areas where lithology, slope, geomorphology, soil permeability and structural features promote infiltration and transmission beneath the soil's surface. The spatial variability of recharge increases its sensitivity to watershed setting, and stresses the need for understanding the geology before determining storage potential or groundwater surface water connections.

The use of spatially explicit approaches has become more significant in the identification of locations and areas that have good recharge and groundwater potential. Zimik et al. (2022) successfully applied GIS-supported analytic hierarchy process techniques to establish potential recharge areas in complicated mountainous landscape using geological, geomorphological, topographic, drainage and land-use parameters. The results show that recharge suitability is a result of the interplay between several watershed characteristics and does not depend on any single watershed parameter. Ghosh et al. (2022) also demonstrated the use of MCDA and AHP in identifying groundwater potential zones in tropical river basin. These studies collectively demonstrate that spatial decision support techniques can be useful in synthesizing the variety of hydrogeological conditions and making them useful for practical recharge and groundwater management considerations.

There is also high temporal variability in recharge dynamics. Goswami and Sekhar (2022) showed some evidence that the groundwater recharge can be significant in tropical hard rock aquifers during short duration hydrological events, suggesting that recharge may not occur on a continuous basis. This behaviour is especially significant in fractured and weathered formations where preferential flow pathways can readily open up when rainfall is heavy. This episodic recharge has the potential to affect approaches based on a single annual or seasonal average rainfall as these are likely to underestimate the significance of event scale infiltration and transient aquifer response. The amount, duration, and rate of rainfall must then be considered along with the subsurface hydraulic properties. Groundwater–surface water exchange is dominated by the same mechanisms under various hydraulic conditions, as shown in Figure 1.

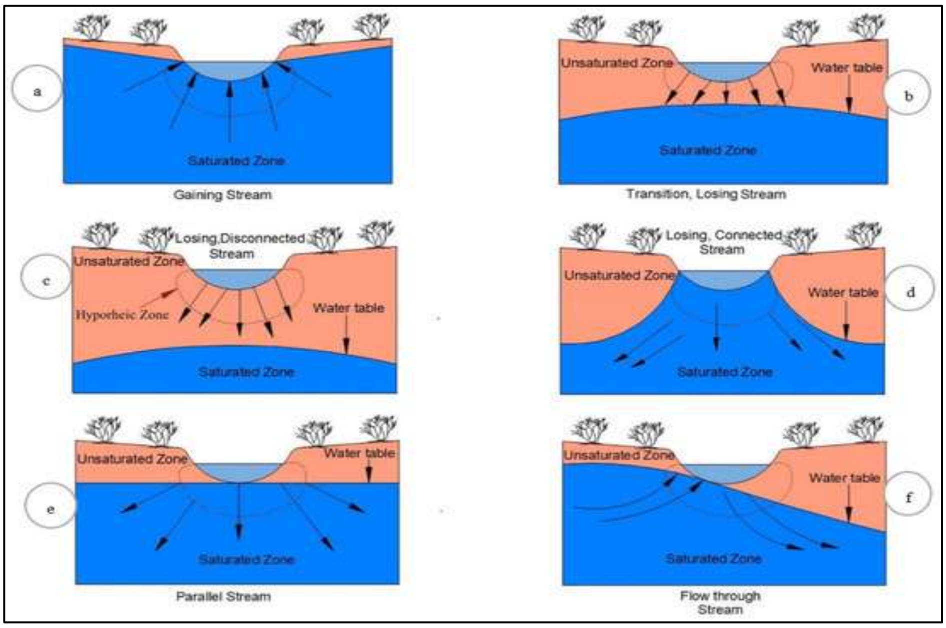

Figure 1. Groundwater–Surface Water Interaction Modes

Source: Adapted from Banerjee and Ganguly (2023)

Geological heterogeneity also influences the origin, flow paths, residence time and evolution of groundwater with seasons. O'Connell et al. (2022) has shown that the combination of geophysical, isotopic and hydrochemical methods can be extremely useful in understanding groundwater processes in a more heterogeneous catchment. Their research indicates that several groundwater sources and pathways can be present in a single watershed, resulting in a distinct hydrochemical signature per source and pathway and that changes in hydrochemical signature can occur across the watershed and even within the watershed over a short period of time. This integrated evidence is of special value to identify recent recharge from older stored water, and to differentiate areas of greater hydrological connectivity. These differences are critical to assess aquifer resilience and groundwater system's ability to provide water supply when recharge decreases.

On a larger catchment, ground water storage and release is critically affected by landscape organization and landscape bedrock. Tafvizi et al. (2022) showed that the landscape properties, subsurface controls, isotope-tracer signals, and flow properties all contribute to the hydrological behavior of Precambrian shield catchments. They conclude that the use of ground water storage should not be considered in isolation from catchment structure. Rather, the storage and flow system functions as a unified whole where the degree of connectivity from recharge areas to aquifers and stream networks is controlled by the geological architecture.

This connectivity is particularly pronounced in periods of low flow. Floriancic et al. (2022) demonstrated the scale dependency of controls on low-flow metrics by catchment characteristics. Therefore, the ability of the subsurface water to be transmitted to channels during dry periods is dependent on the effectiveness of water transmission. Watersheds with more storage capacity and better groundwater–stream connectivity are likely to support baseflow, while those with limited storage and less groundwater–stream connectivity might have rapid flow recession.

In general, the evidence examined reveals that groundwater recharge, storage, and surface water–groundwater interactions are influenced by spatial heterogeneity and temporal variability. The location of recharge is dependent on the geological context, the structure of the aquifer dictates water storage and movement, and the connectivity of the catchments determines when recharge is released to a stream. A combination of geospatial analysis, tracer methods, hydrochemistry and hydrochemistry metrics, then, becomes a more robust foundation for planning for recharge, groundwater allocation, management of low flows, and development of sustainable watershed resources.

5. Implications of Watershed Geology for Command-Area Water Management

Irrigated command areas are very altered hydrological systems in which the supplies through canals, groundwater extraction, drainage and crop management are constantly interacting. Their performance is thus related to the quantity of water supplied as well as to the quality of water distribution, storage, drainage and reuse on the landscape. These processes are affected by the geological and hydrogeological conditions, which include infiltration and groundwater response, seepage losses and susceptibility to water logging and salinity. Sustainable command area management therefore needs to be coordinated and managed not just by the delivery of canal water, but with the management of surface water, groundwater, cropping system and drainage as well.

Water demand and sustainability of irrigation depend to a great extent on crop choice. Pradhan et al. (2022) evaluated Boro rice cultivation in command area of canal irrigation and emphasized to use up the irrigation resource according to the crop water requirement. Canals may be required for watering during dry seasons, adding to the demand, and this may be an added strain on the water resources particularly if groundwater is being used for the same purpose. Balancing production goals with hydrological constraints, the sustainability of command agriculture is thus dependent upon. The availability of irrigation, groundwater conditions, seasonal groundwater recharge and local groundwater system capacity to supply water without depleting the resource should be taken into account when determining cropping decisions. The main, hydrogeological and management factors controlling water dynamics and sustainability in command areas are summarized in Table 2.

Table 2. Hydrogeological and Management Drivers of Command-Area Water Sustainability

Hydrogeological / Management Driver	Effect on Command-Area Water Dynamics	Strategic Management Response
Canal Water Supply	Determines surface-water availability and distribution	Improve allocation and delivery efficiency
Groundwater Abstraction	Influences aquifer storage and seasonal availability	Regulate pumping and promote sustainable withdrawal
Crop Water Demand	Controls pressure on canal and groundwater resources	Promote suitable and less water-intensive cropping systems
On-Farm Irrigation Efficiency	Affects conveyance and application losses	Improve scheduling and field-level irrigation practices
Canal Seepage	Alters groundwater recharge and local water tables	Integrate canal and groundwater management
Drainage Conditions	Influence waterlogging and salinity development	Strengthen surface and subsurface drainage systems
Climate Variability	Changes water availability, recharge, and irrigation demand	Adopt climate-resilient irrigation practices
Groundwater Regulation	Controls long-term aquifer depletion	Combine regulation with farmer incentives
Crop Diversification	Reduces pressure on groundwater-intensive agriculture	Support demand-side water management
Hydrogeological Setting	Governs infiltration, recharge, and subsurface movement	Apply location-specific command-area management

Irrigation efficiency is still the crucial factor at the farm level between water availability and agricultural production. Persistent issues identified by Gupta et al. (2022) in on-farm irrigation water management were: inefficient irrigation application, uneven irrigation water distribution, lack of irrigation infrastructure and lack of adoption of improved irrigation water management. These limits can exacerbate conveyance and application losses, and lead to spatial disparities between head-, middle-, and tail-end users. To realise the actual provision of water to crops, it is therefore important to improve water management in the field. Scheduling more efficiently, better application and better coordination between canal deliveries and field demand can significantly enhance water productivity.

Flexible and resilient irrigation strategies are even more necessary to address climate variability. Sikka et al. (2022) highlighted the importance of water-management practices in the farming sector that have the potential to enhance the climate resiliency of irrigated agriculture. Their analysis is supportive of an integrated approach which includes efficient irrigation, better agronomic practices, water conservation and adaptive resource management. This is particularly critical in areas experiencing variations in rainfall which also vary inflows, recharges and irrigation demands for reservoirs. Water-use efficiency and the ability of farming systems to adapt to variations in water availability are therefore both important for the design of command management that is climate-resilient.

Overwatering can cause as much damage as drought if drainage is not sufficient. For the project command of Tungabhadra, RH et al. (2022) showed the economic importance of subsurface drainage in managing waterlogging and salinity of the soil. Such problems frequently occur when there is a deep channel of resistance or impermeability conditions, shallow groundwater levels, and inadequate natural drainage. Subsurface drainage can be used to restore root-zone conditions and increase the productivity of the land, but whether or not it is feasible depends upon the economic returns and hydrogeological conditions of the area. Drainage should thus be integrated as a key aspect of command-area planning and not as a corrective measure once degradation has happened.

Institutional and behavioural mechanisms are also needed for groundwater management. Bhatia and Singh (2023) analysed a command control approach with incentives in Punjab and found that regulation could be tightened if combined with an incentive to decrease groundwater abstraction. In highly irrigated areas where pumpers' decisions add up to aquifer depletion, this is of special importance. Management frameworks need to therefore incent farmers to conserve resources in a long-term way.

Rathore et al. (2022) also demonstrated that changing cropping systems and optimizing management practices can decrease groundwater consumption and increase economic and environmental sustainability. Their results further highlight the need for demand-side management, in addition to the enhancement of supply and infrastructure. This integrated view also acknowledges that command areas are hydrologically linked landscapes where changes in water use upstream can lead to impacts downstream in terms of aquifer levels, drainage performance, and soil health. To achieve sustainable command-area management, coordination of canal operations, efficient on-farm irrigation, groundwater management, drainage management, climate-smart practices and diversifying crops are needed overall.

If incorporated into the hydrogeological context of a specific command area, these can ameliorate groundwater stress, minimise waterlogging and salinity issues, increase water productivity and increase the long-term resilience of irrigated agriculture.

6. Geospatial Assessment of Groundwater Potential and Watershed Resources

The hydrological conditions vary significantly between geological and geomorphological settings, making geospatial assessment an important aspect of watershed and groundwater-resource evaluation. Lithology, geomorphology, drainage characteristics, soils, land use, lineament density and distribution of surface water all interact to control groundwater occurrence and recharge potential. These spatially heterogenous factors can be effectively combined in a geographic information system (GIS), remote sensing and multi-criteria decision-making approaches. Through their application watershed areas can be mapped for groundwater potential, suitability for recharge and hydrological sensitivity, which facilitates more focused water-resource planning.

Remote sensing can deliver spatial data on the hydrologic aspects of landscapes that affect the presence of groundwater resources, but might be hard to gather comprehensively in the field. Abijith et al. (2020) proved that the multi-criteria analysis using GIS is useful in the identification of groundwater recharge zones for the Ponnaniyaru watershed. The approach allowed multiple thematic layers to be integrated, which allowed the differentiation of areas with different recharge potential. In heterogeneous watersheds, where individual hydrogeological parameters are often not enough to assess the groundwater, such spatial integration is especially valuable. Recharge suitability, on the contrary, is a product of the interaction of surface and subsurface conditions.

Groundwater availability factors have been further systematically weighted using the AHP techniques. Rajesh et al. (2021) used AHP to zone groundwater potential in the Godavari River basin to rank the groundwater occurrence related with the hydrogeological and terrain variables. Similarly, Saravanan et al. (2021) have used remote sensing and GIS to demarcate groundwater-potential zones in Arkavathi sub-watershed. The applications demonstrate the ability of geospatial technologies to convert the complex geological and hydrological data into understandable spatial classes that can help groundwater exploration, recharge planning and prioritization for watersheds.

This is also seen at finer spatial scales with the effectiveness of multi-criteria approaches. The multi-influencing factor method was used in conjunction with AHP to identify groundwater potential zones at micro-level by Sutradhar et al. (2021). The use of alternative weighting methods adds to the interpretability by enabling the effect of several controlling variables to be compared. This is especially beneficial in areas where field observations of groundwater may be sparse or unevenly distributed. They are, however, dependent on the proper selection, weighting and validation of thematic layers.

Topographic complexity imposes extra difficulties in recharge assessments in mountain areas. It is important to consider the terrain, drainage, geological and land-surface properties when using GIS-based AHP for watershed recharge zone mapping as illustrated in the Sikkim Himalayan region by Zimik et al. (2022). Runoff and infiltration may vary greatly on short distances in steep terrain, where topography or structures vary, or under highly variable drainage conditions. Geospatial analysis can then be used to identify favourable recharge areas that might not be identified by surface observations that would otherwise be difficult to identify. Figure 2 shows the spatial results of multi-criteria groundwater assessment, which demonstrates that the groundwater potential in different areas of the basin is widely divergent from Very Low to Very High groundwater potential zones.

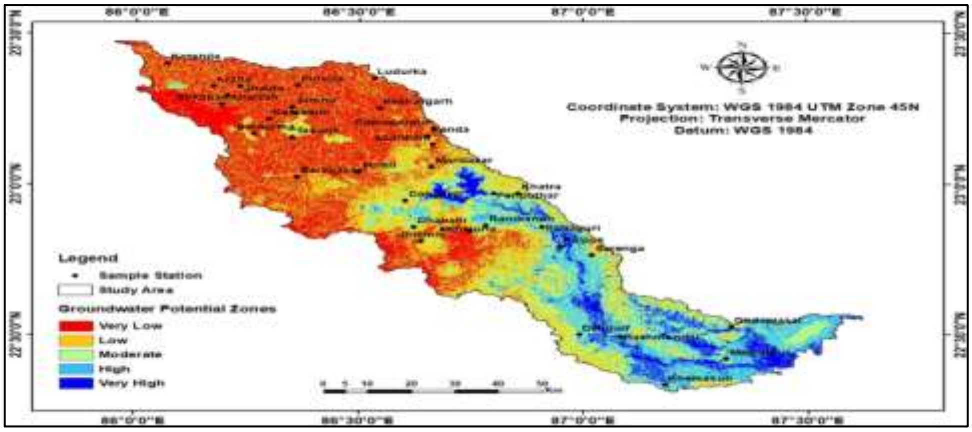

Figure 2. Spatial distribution of groundwater potential zones derived through GIS-based multi-criteria assessment

Source: Adapted from Zimik et al. (2022)

Some of the same techniques have been used in tropical river basins. In a study by Ghosh et al. (2022), the groundwater potential zones were evaluated using the MCDA and AHP techniques, highlighting that groundwater potential is influenced by a combination of various hydrogeological factors. Sahu et al. (2022) furthered this approach by correlating the groundwater recharge-potential mapping with identification of appropriate groundwater recharge structures. This is an important step from resource assessment to application in management as spatial information can be used directly to inform placement of interventions designed to improve infiltration and aquifer recharge.

Although the models are useful, they should not be used as an alternative to field-based hydrogeological investigation.

Final groundwater potential maps can be affected by the assigned weights, quality of input datasets, spatial resolution and classification methods. Groundwater-level observations, well yields, measurements of recharge, or other field-based evidence of validation, are then necessary to enhance reliability.
In general, GIS, remote sensing, AHP and MCDA are a very strong tool for integrating geological and hydrological information throughout the watershed landscape. Together, they can be used for groundwater-potential mapping, identification of recharge zones, watershed prioritization, and recharge interventions that can be implemented. In combination with field validation, these methods can enhance spatial decision-making and ensure science-based sustainable groundwater development and watershed-resource management.

7. Integrated Groundwater Governance and Sustainable Water Management in Watershed–Command Systems
There is a growing need to integrate knowledge of the hydrogeology with watershed and command area water resources planning, management and regulation, water quality analysis, and climate adaptation to achieve sustainable management of water. The location of groundwater storage and transmission is a function of geological controls while the long-term sustainability relies on interactions of abstraction, irrigation demand, recharge, and institutional decisions. Recent studies instead, however, suggest that approaches to groundwater management more than the mere assessment of groundwater availability at the point of extraction link aquifer behaviour, surface-water usage, agricultural demand, and governance at the basin and command area level.
An important aspect of this holistic view is water quality. Monika et al. (2024) in the review on suitability of groundwater and surface water for irrigation in Sundarban region observed that not only water quantity, but also water quality (in terms of chemical suitability) and its effect on soil and crop productivity is to be considered while planning for irrigation. Groundwater could be constrained due to salinity and other hydrochemical issues in coastal and deltaic areas and source selection and conjunctive use becomes even more critical. This shows that before the expansion of irrigation and/or groundwater development, hydrogeological assessment should consider both the potential for water storage and the water quality.
Groundwater development may be more feasible in some areas and less feasible in others, which can be identified through the use of spatial decision-support tools. Borah and Bora (2025) used MCDA-AHP techniques to explore groundwater in a watershed environment of North-East India, illustrating the utility of using multiple geological, geomorphological and hydrological factors to delineate groundwater-potential zones. These methods are useful for prioritizing exploration and recharge interventions, and monitoring, especially when field observations are limited. The groundwater-potential mapping however needs to be linked to recharge and abstraction estimates so as not to turn high-potential areas into areas of abstraction in the future.
Rizvi et al. (2025) highlighted the effects of over-abstraction in their study on the groundwater exploitation, depletion, and management in the context of agriculture productivity in India. Their synthesis shows that the groundwater-fed agriculture will fail to be sustainable if groundwater extraction is continuously higher than the recharge. This forms a demand management, efficient irrigation, crop adjust, artificial recharge and coordinated use of surface water and groundwater. The challenge is not, however, just to find groundwater, but to balance groundwater withdrawals with aquifer recovery and ensure agricultural livelihoods are protected.
It is also critical that appropriate institutional structures are established. Sarkar and Sarkar (2025) documented the evolution of groundwater irrigation and groundwater policies in India, and how groundwater's spatial dispersion, private access, and close association with agricultural production makes it extremely challenging to govern. Monitoring, incentives, energy and irrigation policies, and locally appropriate management arrangements are essential to enable regulatory measures to be effective in achieving groundwater governance. Hydrogeological information is particularly valuable if the governance units are not only administrative, but also closely correspond to aquifer and watershed boundaries.
The groundwater-flow model is another tool to help enhance canal command management. Shukla et al. (2025) simulated the groundwater flow in the command of Indira Sagar canal, highlighting the need to consider aquifer response in irrigated landscapes. Groundwater-level change and potential canal recharge, pumping effects and susceptibility to excessive groundwater-level rise or fall can be evaluated using such modelling. It is therefore a tool to facilitate conjunctive use planning and to balance the use of canal supply and groundwater extraction.
These interactions are further complicated by the variability of climate. Eldho et al. (2023) demonstrated that sustainable management of water in agricultural production in a changing climate would need to be adaptive to the changing water availability and irrigation demand. The combination of these studies provides the basis for an integrated management strategy that involves hydrogeological assessment, water-quality evaluation, geospatial targeting, groundwater-flow modelling, demand management and effective governance. Integration can lead to an increase in resilience, mitigation of depletion and salinity hazards, and better match between agricultural water use and the capacity of watershed and command-area systems in the long term. This will help enhance planning at all scales – seasonal, spatial, institutional – and help secure long-term water security.

8. Conclusion
Geologic and hydrogeologic conditions play a significant role in the watershed hydrology and command-area water management, affecting infiltration, recharge of groundwater, subsurface storage, generation of runoff, baseflow changes, and exchange of surface water and groundwater. Available data suggest that the physical characteristics of the lithology, geomorphology, fractures, aquifer properties, slope, drainage characteristics, and geological heterogeneity result in significant spatial variability in hydrologic response. All these differences have an immediate

bearing on the availability of ground water, the efficiency of recharge, the reliability of irrigation and susceptibility to water logging, salinity and depletion of aquifers. The use of geospatial techniques, such as GIS, remote sensing, AHP, and MCDA, has enhanced the delineation of groundwater-potential and recharge zones, and tracer, hydrochemical, geophysical, and modelling techniques have enhanced understanding of groundwater connectivity and groundwater dynamics. Thus, sustainable management calls for incorporating the geological information in irrigation planning, selecting the right crop, managing its drainage, regulating groundwater and adapting to climate change. The management of command areas must be based on a holistic approach of surface-subsurface systems instead of viewing each command area as an individual canal system. More attention should be paid to field validation, aquifer-scale monitoring, conjunctive water use and site-specific recharge interventions. A water use efficiency, groundwater stress reduction, long-term water security, and irrigation adaptation and resilience can be achieved in watershed and command-area environments through integration of hydrogeological assessment with spatial decision support tools and adaptive governance. Future research should further develop the integration of watershed processes, aquifer responses, irrigation operation with climate variability across scales.

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