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ASSESSMENT OF URBANIZATION IMPACTS ON GROUNDWATER QUALITY USING WQI, NPI, REMOTE SENSING AND GIS IN SHAIKPET, HYDERABAD, INDIA

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Abstract: **Rapid urbanization exerts considerable pressure on ground water resources through increasing groundwater abstraction, reduction in natural recharge, expansion of impervious surfaces, wastewater infiltration, construction activities, and urban runoff. The present investigation evaluates the impact of urbanization on groundwater quality in and around the Shaikpet region of Hyderabad, Telangana, India, using an integrated physicochemical, Water Quality Index (WQI), Nemerow Pollution Index (NPI), Remote Sensing (RS), and Geographic Information System (GIS) approach. Twenty-three representative groundwater sampling locations were considered during 2022 and 2023, and major physicochemical parameters including pH, electrical conductivity (EC), total dis solved solids (TDS), total hardness (TH), calcium, magnesium, alkalinity, chloride, sulphate, nitrate, sodium, potassium, and fluoride were evaluated. The WQI results indicate that the groundwater quality is predominantly poor, with 21 stations classified as poor and two stations classified as very poor. The WQI values reported for representative locations range from 133.89 to 256.79 during the comparative assessment. The highest 2023 WQI was observed at Valli High School (S19), indicating a highly stressed urban environment. NPI analysis further identified Saibaba Temple (S7), Sri Peddamma Talli Temple (S17), Valli High School (S19), Aziz Bagh Colony (S22), and The Life Church (S23) as important pollution hotspots. Remote sensing and GIS analysis showed that built-up land occupies approximately 70% of the study area, while vegetation, wasteland, water bodies, and agricultural land account for approximately 13.97%, 10%, 5%, and 1.03%, respectively. The integrated analysis demonstrates that urban expansion, wastewater leakage, construction activities, reduced recharge, and runoff are important factors controlling groundwater quality. Protection of recharge zones, improved wastewater management, artificial recharge, and continuous groundwater monitoring are therefore recommended for sustainable groundwater management.**

Keywords: **Groundwater quality; Urbanization; Shaikpet; Water Quality Index; Nemerow Pollution Index; Remote Sensing; GIS; Hyderabad; groundwater pollution; spatial analysis.**

I. INTRODUCTION

Groundwater is one of the most important freshwater resources for domestic, industrial, agricultural, and institutional requirements. In rapidly urbanizing regions, groundwater systems are exposed to increasing anthropogenic pressure because of population growth, infrastructure development, land use transformation, wastewater generation, and groundwater abstraction. Urbanization modifies the natural hydrological cycle by replacing permeable surfaces with buildings, roads, pavements, and other impervious structures. Consequently, surface runoff increases, while natural infiltration and ground water recharge decline.

The deterioration of groundwater quality is generally associated with the combined effects of natural hydrogeochemical processes and anthropogenic activities. Dissolution of minerals from geological formations can increase the concentrations of calcium, magnesium, fluoride, sulphate, and other ions. At the same time, domestic sewage, septic tanks, commercial activities, construction materials, road runoff, and improper solid-waste disposal can introduce nitrate, chloride, dissolved solids, and other contaminants into groundwater.

The Shaikpet region of Hyderabad has experienced substantial urban development over recent decades. Residential colonies, commercial establishments, educational institutions, religious structures, transportation corridors, and infrastructure projects have expanded rapidly. Such development has altered the natural drainage and recharge characteristics of the region and increased the demand for groundwater.

Conventional assessment based on individual physicochemi cal parameters may not adequately represent the overall status of groundwater. Therefore, integrated indices such as the Water Quality Index (WQI) and Nemerow Pollution Index (NPI) provide useful approaches for summarizing the effects of multiple water quality parameters.

Remote Sensing and Geographic Information System techniques further enable the spatial relationship between urban land-use change, geological characteristics, drainage, terrain, recharge conditions, and groundwater quality to be investigated.

The objectives of the present study are therefore:

(i) to evaluate the physicochemical characteristics of groundwater in the Shaikpet region;
(ii) to assess groundwater suitability using WQI;
(iii) to evaluate pollution intensity using NPI;
(iv) to investigate the spatial influence of urbanization using RS and GIS;
(v) to identify groundwater pollution hotspots; and
(vi) to propose measures for sustainable groundwater management.

II. LITERATURE SURVEY

Groundwater quality in rapidly urbanizing regions is controlled by the combined effects of hydrogeological conditions, land-use transformation, wastewater generation, groundwater abstraction, and natural water–rock interaction. In hard-rock terrains, fractures and weathered zones can enhance ground water movement while simultaneously providing preferential pathways for contaminant migration. Therefore, groundwater quality assessment requires the integration of physicochemical analysis with spatial and hydrogeological information.

Early studies in Hyderabad demonstrated the usefulness of integrating remote sensing and GIS with groundwater-quality measurements. Asadi et al. investigated groundwater quality in Zone-III of the Municipal Corporation of Hyderabad and demonstrated that spatial groundwater-quality patterns could be related to land-use characteristics using remote sensing and GIS techniques [4]. Similarly, Vuppala et al. evaluated groundwater quality in another part of Hyderabad using re mote sensing, GIS, physicochemical analysis, and WQI. Their results indicated that substantial portions of the study region exhibited poor to very poor groundwater quality, highlighting the importance of urban land-use patterns in groundwater assessment [5].

Khan et al. investigated the impact of land-use changes on groundwater quality in the Maheshwaram watershed near Hyderabad. Their study demonstrated that rapid expansion of built-up areas, together with unsewered sanitation and other anthropogenic activities, was associated with deterioration of groundwater quality [6]. The study also demonstrated the usefulness of integrating groundwater-quality indices with GIS for identifying areas of groundwater-quality stress. These findings are particularly relevant to rapidly urbanizing parts of the Hyderabad metropolitan region.

Groundwater vulnerability in granitic terrains around Hyderabad has also been investigated from a resource-management perspective. Studies have reported elevated concentrations of fluoride, nitrate, and electrical conductivity in parts of the Hyderabad region and emphasized the need for spatially differentiated groundwater-management strategies [7]. Such results demonstrate that groundwater-quality deterioration may arise from the combined influence of natural hydrogeochemi cal processes and anthropogenic activities.

Adimalla and Taloor investigated groundwater quality in the hard-rock terrain of Medak, Telangana, using GIS and groundwater-quality index techniques [8]. Their findings showed that groundwater chemistry was strongly influenced by rock weathering and hydrogeochemical processes. The study demonstrates the importance of considering geological controls while interpreting groundwater-quality indices in southern Indian hard-rock environments.

Water Quality Index has been widely adopted for reducing multiple physicochemical parameters into a single indicator of drinking-water suitability. Ram et al. applied WQI within a GIS framework to assess groundwater quality in the hard-rock terrain of Mahoba, Uttar Pradesh [9]. Their study showed that spatial WQI assessment can effectively identify localized groundwater-quality problems and support water resource management.

Similarly, groundwater-quality assessment in the Bokaro district used GIS-based WQI together with BIS and WHO standards to evaluate the suitability of groundwater for drinking purposes [10]. The results demonstrated considerable spatial variability in groundwater quality and emphasized the usefulness of seasonal and spatial assessment.

Geospatial and statistical approaches have also been increasingly combined for groundwater-quality evaluation. A study of groundwater in Faridabad and Gurgaon used geospatial mapping, WQI, correlation analysis, and principal component analysis to investigate groundwater-quality variation in rapidly urbanizing areas [12]. Such integrated approaches provide better insight into the distinction between natural hydro geochemical controls and anthropogenic sources.

Remote sensing and GIS have further been applied to spatially map groundwater-quality indices and individual contaminants. Studies using multiple physicochemical parameters have shown that GIS interpolation can reveal localized zones of poor and very poor groundwater quality [11]. The integration of remote sensing-derived land-use information with groundwater-quality data therefore provides a useful frame work for understanding the relationship between urban expansion and groundwater deterioration.

The influence of urbanization on groundwater quality has also been reported in other rapidly developing Indian regions. Recent studies indicate that increased built-up surfaces, wastewater generation, impervious cover, and inadequate drainage can increase contaminant loading while simultaneously reducing natural groundwater recharge [13]. Urban groundwater systems are consequently affected by both declining recharge efficiency and increasing pollutant loading.

The literature indicates that groundwater quality is controlled by two broad groups of processes. Natural processes include mineral dissolution, rock weathering, ion exchange, and groundwater–rock interaction, whereas anthropogenic processes include sewage leakage, septic-system contamination, urban runoff, construction activity, industrial discharge, and excessive groundwater abstraction. Consequently, parameters such as EC, TDS, hardness, chloride, sulphate, nitrate, and fluoride are frequently used as indicators of groundwater-quality deterioration [18–20].

Although several investigations have examined groundwater quality in Hyderabad and other rapidly urbanizing regions of India, relatively limited attention has been given to integrating detailed urban land-use characteristics, groundwater-quality indices, pollution hotspots, and local hydrogeological controls at the neighbourhood scale. In particular, a focused assessment of the Shaikpet region that combines RS-GIS analysis, physicochemical characterization, WQI, Nemerow Pollution Index, and temporal comparison can provide a more detailed understanding of localized groundwater degradation.

The present study therefore addresses this gap by integrating groundwater-quality measurements from 23 sampling locations with land-use/land-cover, terrain, drainage, geological, and spatial information. WQI is used to assess overall drinking-water suitability, whereas NPI is used to identify locations experiencing relatively severe pollution. The combined RS-GIS and groundwater-quality framework is intended to identify pollution hotspots and clarify the relationship between rapid urbanization, reduced recharge, anthropogenic contaminant loading, and groundwater-quality deterioration in the Shaikpet region.

III. STUDY AREA

The study area is situated in the western part of Hyderabad, Telangana, India, within the rapidly urbanizing Shaikpet region. The study boundary covers approximately 18.5 $km^2$and includes residential, commercial, institutional, and mixed urban land-use areas. The central location of Shaikpet is approximately 17.404°N latitude and 78.399°E longitude. The study area is characterized by dense urban development and extensive built-up surfaces, making it suitable for assessing the influence of urbanization on groundwater quality.

The regional geological setting is dominated by Precambrian crystalline rocks consisting mainly of pink and grey granites and granite gneisses. The granitic terrain is characterized by weathered zones, fractures, joints, faults, fissures, and locally occurring dykes, which strongly influence groundwater occurrence, movement, and storage. Groundwater occurs predominantly under phreatic conditions within the weathered zone and under semi-confined to confined conditions within fractured rock formations. In the Hyderabad region, groundwater development is mainly through shallow and deep bore wells, with borewell depths reported in the range of approximately 100–300 m. These geological and hydrogeological characteristics are important controls on the spatial distribution of groundwater quality in the study area. [16]

The terrain is generally undulating and is characterized by granite hillocks, low-lying areas, and localized drainage channels. The hydrogeological framework is further influenced by seasonal rainfall, surface runoff, recharge through weathered and fractured zones, and groundwater abstraction. Several water bodies and drainage features occur within and around the Shaikpet region; for example, government records identify Chiran Kunta and the Banjara Hills pond within Shaikpetmandal. These surface-water features can contribute to localized recharge during the monsoon season. [17]

Rapid urbanization has substantially modified the natural hydrological system. Expansion of residential colonies, commercial establishments, roads, educational institutions, religious structures, and other infrastructure has increased the proportion of impervious surfaces. Consequently, rainfall infiltration and natural groundwater recharge are locally reduced, while urban runoff, wastewater leakage, and anthropogenic contaminant loading may increase the vulnerability of shallow groundwater. The interaction between urban land use, hydrogeological conditions, and groundwater abstraction therefore provides an important basis for evaluating groundwater-quality variations in the present study.

Table 1: Groundwater sampling stations considered in the study

Station	Location	Station	Location
S1	Shaikpet	S13	Toli Chowki
S2	Hakeempet	S14	Rai Durga
S3	Bakhtawarguda	S15	Nijam Colony
S4	IAS Colony	S16	MLA Colony
S5	Nijam Colony	S17	Sri Peddamma Talli Temple
S6	Naagamma Temple	S18	Cheruvu Murthy Colony
S7	Saibaba Temple	S19	Valli High School
S8	Khajaguda	S20	Falcon Valley Mosque
S9	Manikonda	S21	G. Narayanamma Institute
S10	Puppalaguda	S22	Aziz Bagh Colony
S11	Neknampur	S23	The Life Church
S12	Narsingi		

IV. MATERIALS AND METHODS

4.1 Groundwater Sampling

A total of 23 representative groundwater sampling locations were selected within the study area to capture the spatial variability of groundwater quality under different urban land-use conditions. The sampling locations represent residential, commercial, institutional, religious, and rapidly urbanizing environments. The locations were selected to provide adequate spatial coverage of the study region and to represent areas subject to different levels of anthropogenic influence.

Groundwater samples were collected during the respective monitoring seasons of 2022 and 2023. The sampling locations were recorded using geographic coordinates obtained using a Global Positioning System (GPS). The sampling stations considered in the study are presented in Table 1.

4.2 Physicochemical Analysis

The groundwater samples were evaluated for pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), calcium, magnesium, total alkalinity (TA), chloride, sulphate, nitrate, sodium, potassium, and fluoride. These parameters were selected because they provide an integrated indication of groundwater mineralization, salinity, hardness, nutrient enrichment, and potential anthropogenic contamination.

The physicochemical analyses were carried out using standard analytical procedures prescribed in the Standard Methods for the Examination of Water and Wastewater published by APHA, AWWA and WEF [18]. The measured concentrations were subsequently compared with the applicable drinking water quality guidelines and standards specified by the World Health Organization (WHO) and Bureau of Indian Standards (BIS) [19, 20].

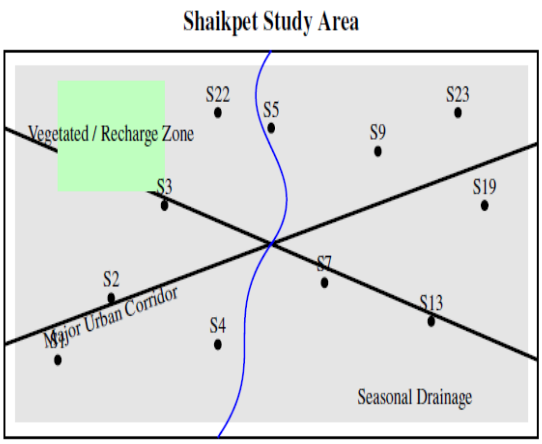

Figure 1: Conceptual spatial representation of urban land use, drainage, recharge zones, and groundwater sampling locations in and around the Shaikpet study area.

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Table 2: Groundwater parameters and their environmental significance

Parameter	Symbol	Environmental significance
p^H	p^H	Acidity or alkalinity of groundwater
Electrical Conductivity	EC	Dissolved ionic concentration
Total Dissolved Solids	TDS	Total dissolved mineral content
Total Hardness	TH	Mainly related to Ca and Mg
Calcium	Ca^{2+}	Geological and mineral dissolution
Magnesium	Mg^{2+}	Rock weathering and mineral dissolution
Total Alkalinity	TA	Buffering capacity of groundwater
Chloride	Cl^-	Domestic wastewater and urban runoff
Sulphate	SO_4^{2-}	Mineral dissolution and wastewater inputs
Nitrate	NO_3^-	Sewage and septic contamination
Sodium	Na^+	Domestic wastewater and mineral sources
Potassium	K^+	Domestic and anthropogenic sources
Fluoride	F^-	Geological source and water–rock interaction

V. REMOTE SENSING AND GIS METHODOLOGY

Remote sensing and Geographic Information System (GIS) techniques were employed to evaluate the spatial characteristics of the study area and to investigate the relationship between urbanization and groundwater quality. The GIS frame work integrated groundwater-quality observations with land use/land-cover, geological, topographic, and drainage information.

Landsat-8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) imagery was considered for land-use/land cover characterization [21]. Sentinel-2 MultiSpectral Instrument (MSI) imagery was also used to provide multispectral information for spatial characterization of the study area [22]. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data were used to derive elevation, slope, and drainage characteristics [23].

The spatial datasets were georeferenced and projected into a common coordinate reference system before analysis. The geographic coordinates of the 23 groundwater sampling stations were incorporated into the GIS environment and linked with the corresponding physicochemical observations. Geological maps, topographic information, satellite imagery, DEM Table derived terrain parameters, and groundwater-quality data were integrated to identify spatial patterns and areas potentially influenced by urban development.

Table 3: Remote sensing and GIS datasets used in the study Dataset Source Application

Dataset	Source	Application
Landsat-8 OLI/TIRS	USGS	Land-use/land-cover classification
Sentinel-2 MSI	ESA	Urban and vegetation mapping
SRTM DEM (30m)	NASA	Elevation, slope, and drainage analysis
Geological Map	GSI	Lithological and structural interpretation
Topographic Sheets	Survey of India	Base-map preparation
GPS Coordinates	Field Survey	Groundwater sampling location mapping
Groundwater Data	Laboratory Analysis	Water-quality and WQI mapping

5.1 Remote Sensing and GIS Datasets

Multiple spatial and non-spatial datasets were integrated to evaluate the relationship between urbanization and groundwater quality. Satellite imagery, digital elevation data, geological information, topographic data, field observations, and laboratory groundwater-quality data were integrated within the GIS environment. The datasets and their respective applications are summarized in Table 3.

5.2 Spatial Interpolation

The spatial distribution of individual groundwater-quality parameters was generated using the Inverse Distance Weighted (IDW) interpolation technique. IDW estimates the value of an unsampled location from surrounding measured observations, with the influence of each sampling point decreasing as its distance from the prediction location increases [24].

For a prediction location $x0$, the estimated value was calculated using the weighted average of the surrounding observations as

$$Z(x_0) = \frac{\sum_{i=1}^{n} w_i Z(x_i)}{\sum_{i=1}^{n} w_i}, \quad (1)$$

where $Z(x0)$ is the estimated value at the unsampled location, $Z(xi)$ is the measured value at sampling location i, and wi is the distance-based weight. The weight was defined as

$$w_i = \frac{1}{d_i^P}, \quad (2)$$

where di is the distance between the prediction location and the ith sampling point, and p is the power parameter controlling the rate at which the influence of a sampling point decreases with distance [24].

The IDW method was applied to the measured groundwater quality parameters to generate continuous spatial-distribution surfaces for the study area. The resulting thematic maps were used to identify areas of relatively low, moderate, and high parameter concentrations and to delineate potential groundwater-quality hotspots.

5.3 Groundwater Quality Assessment

The interpolated groundwater-quality surfaces were analysed together with the sampling-point observations to evaluate spatial and temporal variations in groundwater chemistry. The Water Quality Index (WQI) and other groundwater-quality indicators were subsequently used to integrate multiple physicochemical parameters and classify the overall suitability of groundwater for drinking purposes.

The GIS outputs were further compared with land-use/land cover, geological, topographic, and hydrogeological characteristics to identify possible relationships between urbanization and groundwater quality deterioration. Areas exhibiting elevated concentrations of multiple groundwater-quality parameters were considered potential groundwater-quality hotspots and were examined in relation to local urban activities and hydrogeological conditions.

5.4 Land Use/Land Cover

Land-use/land-cover (LULC) classification was performed using multispectral satellite imagery to characterize the spatial pattern of urban development and other major surface-cover classes within the study area. The classification included built up land, vegetation, wasteland, water bodies, and agricultural land.

The LULC analysis indicates that built-up land constitutes the dominant land-cover class within the study area, accounting for approximately 70% of the total area. Vegetation accounts for approximately 13.97%, while wasteland, water bodies, and agricultural land account for approximately 10%, 5%, and 1.03%, respectively.

The dominance of built-up land indicates a high degree of urban development within the study region. The extensive impervious surface coverage can reduce natural infiltration and modify surface-water runoff, thereby influencing groundwater recharge conditions. In addition, densely developed areas may increase the potential for wastewater leakage, sewage infiltration, and other anthropogenic inputs to the shallow groundwater system.

The spatial distribution of the LULC classes was subsequently compared with groundwater-quality maps to examine the possible influence of urban land-use patterns on the distribution of EC, TDS, chloride, nitrate, sulphate, and other groundwater quality parameters.

The dominance of built-up land indicates intensive urbanization.

The limited agricultural area and reduction in natural permeable surfaces indicate increasing pressure on groundwater recharge.

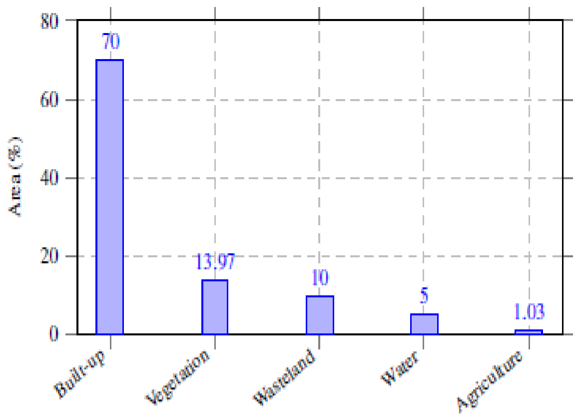

Figure 2: Land-use/land-cover distribution of the Shaikpet study area.

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Table 4: WQI classification used for groundwater assessment

WQI Range	Class	Drinking suitability
< 50	Excellent	Suitable without treatment
50–100	Good	Suitable for drinking
100–200	Poor	Treatment required
200–300	Very Poor	Extensive treatment required
> 300	Unsuitable	Not recommended

Table 5: Representative WQI values of groundwater stations

Station	Location	WQI	Category
S5	Nijam Colony	138.35	Poor
S2	Hakeempet	145.72	Poor
S1	Shaikpet	150.80	Poor
S9	Manikonda	151.52	Poor
S4	IAS Colony	153.64	Poor
S10	Puppalaguda	154.03	Poor
S12	Narsingi	158.24	Poor
S8	Khajaguda	165.72	Poor
S16	MLA Colony	175.02	Poor
S17	Sri Peddamma Talli Temple	178.12	Poor
S3	Bakhtawarguda	189.46	Poor
S23	The Life Church	204.77	Very Poor
S22	Aziz Bagh Colony	205.63	Very Poor

VI. WATER QUALITY INDEX

The Water Quality Index (WQI) integrates multiple physicochemical parameters into a single numerical indicator of groundwater suitability. The weighted arithmetic formulation is expressed as

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}, \tag{3}$$

where Wi is the relative weight assigned to parameter i and Qi is its corresponding quality rating. The quality rating is calculated as

$$Q_i = \frac{C_i}{S_i} \times 100, \tag{4}$$

where Ci is the measured concentration and Si is the corresponding standard or permissible concentration.

6.1 WQI Results

The WQI results indicate that most groundwater stations fall within the poor category. Representative values are presented in Table 5.

Table 6: Nemerow Pollution Index classification

NPI Range	Category	Groundwater status
< 1	Low	Acceptable quality
1–2	Moderate	Slight contamination
2–3	Significant	Moderately contaminated
3–5	High	Highly contaminated
> 5	Severe	Heavily polluted

Table 7: Major groundwater pollution hotspots identified us ing NPI

Station	Location	NPI	Major urban influence
S7	Saibaba Temple	7.26	Religious activity and sewage leakage
S17	Sri Peddamma Talli Temple	6.03	Domestic wastewater and settlements
S19	Valli High School	5.94	Dense development and drainage problems
S22	Aziz Bagh Colony	> 3	Urban runoff and household wastewater
S23	The Life Church	> 3	Commercial activity and poor drainage

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The overall WQI assessment indicates that 21 stations are classified as poor and two stations as very poor, indicating the need for appropriate treatment before drinking use.

VII. NEMEROW POLLUTION INDEX

Nemerow's Pollution Index (NPI) provides an integrated representation of groundwater pollution by comparing observed concentrations with corresponding standards. For parameter i,

$$P_i = \frac{C_i}{S_i}, \quad (5)$$

7.1 NPI Pollution Hotspots

The highest NPI values occur at locations associated with intense urban activity.

The NPI values greater than 5 at S7, S17, and S19 indicate severe pollution according to the adopted classification. These locations therefore require priority groundwater monitoring and pollution control.

VIII. MAJOR GROUNDWATER QUALITY PARAMETERS INFLUENCING POLLUTION

Several physicochemical parameters contribute to groundwater-quality deterioration.

Electrical conductivity and TDS are particularly useful indicators of increased dissolved ionic loading. Nitrate and chloride indicate anthropogenic contamination, particularly where wastewater and septic leakage occur. Calcium and magnesium reflect both geological weathering and construction-related processes.

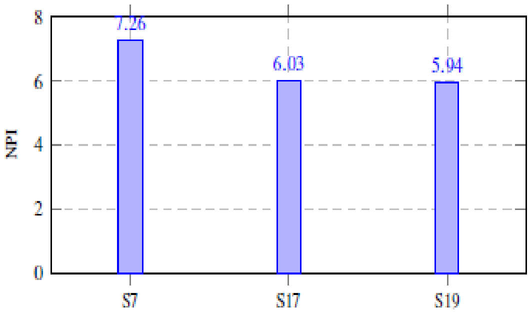

Figure 3: Highest reported NPI values at major groundwater pollution hotspots.

Table 8: Major parameters contributing to elevated NPI values

Parameter	Major source	Urban influence
EC	Dissolved ionic salts	Sewage leakage and urban runoff
TDS	Mineral salts	Wastewater infiltration and construction
Ca^{2+}	Cement and rock dissolution	Infrastructure development
Mg^{2+}	Rock weathering	Domestic wastewater discharge
SO_4^{2-}	Industrial/sewage sources	Urban wastewater contamination
NO^{-3}	Organic waste	Septic leakage and sewage infiltration
Cl^-	Domestic wastewater	Urban runoff and drainage discharge
F^-	Fluoride-bearing minerals	Groundwater over-extraction

Table 9: Major urban factors affecting groundwater quality

Urban activity	Affected parameters	Groundwater impact
Residential expansion	EC, TDS, NO_3–	Wastewater and increased abstraction
Commercial development	EC, SO_4^{2-}, TDS	Chemical and wastewater enrichment
Construction activities	TH, Ca^{2+}, Mg^{2+}	Mineral and construction material dissolution
Religious institutions	EC, TDS, Cl^-	Localized wastewater accumulation
Sewage leakage	NO_3^-, Cl^-	Direct contamination
Road runoff	Na^+, Cl^-	Salt accumulation and increased conductivity
Impervious surfaces	EC, TDS	Reduced recharge and pollutant concentration
Groundwater over-extraction	F^-	Enhanced interaction with fluoride-bearing minerals

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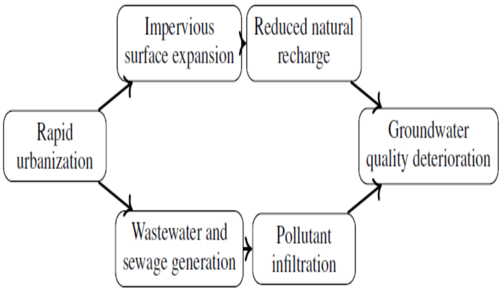

Figure 4: Conceptual relationship between urbanization and groundwater quality deterioration.

IX. INFLUENCE OF URBANIZATION ON GROUNDWATER QUALITY

Urbanization affects groundwater through several interconnected mechanisms. The urbanization–groundwater relationship is conceptually represented in Figure 4.

Table 10: Major thematic layers generated using RS and GIS

Thematic layer	**Purpose**
LULC	Urbanization and land transformation analysis
Geology	Lithological and structural characterization
Geomorphology	Groundwater occurrence assessment
Drainage network	Surface runoff and recharge assessment
Slope	Groundwater recharge potential
DEM	Terrain and elevation analysis
Lineament density	Groundwater potential and fracture mapping
Groundwater quality maps	Spatial distribution of parameters
WQI	Overall drinking-water suitability
NPI	Spatial pollution assessment

Table 11: Spatial distribution of major NPI-based contamination indicators

Parameter	**Affected stations**	**Status**	**Possible source**
EC	S3, S4, S5, S7, S8, S9, S15, S16,S22	High	Urban runoff and sewage leakage
TDS	S3, S6, S7, S9, S18, S22, S23	High	Wastewater infiltration
TH	S4, S8, S12, S18, S20, S21	High	Construction and mineral dissolution
SO_4^{2-}	S11, S14	Above limit	Industrial discharge and sewage
NO_3^-	S13, S14, S16, S19	High	Septic leakage and domestic sewage
Cl^-	Majority of stations	High	Urban runoff and household waste
F^-	S7, S10, S11, S13, S17, S21, S23	High	Geological formations

X. GIS-BASED SPATIAL ASSESSMENT

The integrated RS-GIS analysis considered several thematic layers.
The spatial analysis indicates that geological structures influence groundwater occurrence, whereas urbanization has a stronger influence on groundwater quality. Fractured and weathered zones can provide preferential pathways for groundwater movement and recharge. Conversely, highly urbanized zones with impervious surfaces can restrict infiltration while increasing surface runoff.

XI. SPATIAL DISTRIBUTION OF MAJOR CONTAMINANTS

The spatial pattern suggests that groundwater contamination is not controlled by a single source. Instead, multiple urban and geological processes interact to determine groundwater chemistry.

XII. OVERALL RESULTS AND DISCUSSION

The integrated analysis reveals a clear association between urban development and groundwater-quality deterioration.
First, the high proportion of built-up land demonstrates the intensity of urbanization. Approximately 70% of the study area is classified as built-up, substantially reducing natural infiltration surfaces.
Second, WQI analysis indicates that groundwater quality is predominantly poor. The reported distribution contains 21 poor-quality stations and two very-poor stations, indicating that groundwater at most locations requires treatment before drinking.
Third, temporal comparison demonstrates that several locations exhibit increasing WQI values in 2023. The increase at S19 is particularly important, with WQI increasing from 198.47 to 256.79. S7 also shows a substantial increase from 188.03 to 236.33.
Fourth, NPI analysis identifies several pollution hotspots. The highest reported NPI value is 7.26 at S7, followed by

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6.03 at S17 and 5.94 at S19. These values fall within the severe pollution category.

Table 12: Summary of major findings

Indicator	Major finding
Study area	Approximately 18.5 km^2
Sampling stations	23
Built-up land	Approximately 70%
Vegetation	Approximately 13.97%
Wasteland	Approximately 10%
Water bodies	Approximately 5%
Agricultural land	Approximately 1.03%
Overall WQI status	Predominantly poor to very poor
Poor WQI stations	21
Very poor WQI stations	2
Highest listed 2023 WQI	S19 = 256.79
Lowest listed 2023 WQI	S1 = 133.89
Highest NPI	S7 = 7.26
Major pollution indicators	EC, TDS, TH, NO_3^-, Cl^-, F^-
Major urban pressures	Sewage, runoff, construction, and reduced recharge

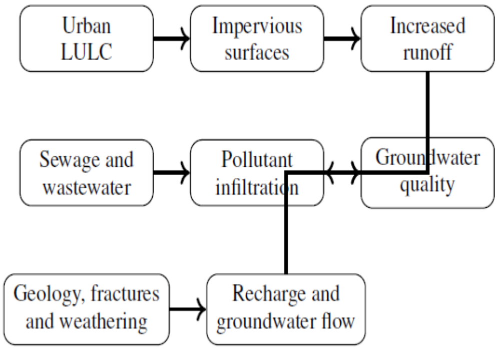

Figure 5: Integrated conceptual model linking urbanization, hydrogeology, and groundwater-quality deterioration.

The simultaneous occurrence of high WQI and high NPI at several urban locations indicates that groundwater degradation is likely associated with multiple anthropogenic pressures, including wastewater infiltration, urban drainage problems, construction, and dense settlement.

XIII. CONCEPTUAL MODEL OF GROUNDWATER DETERIORATION

The overall groundwater system can be understood as an interaction between urban land-use transformation, hydrogeological characteristics, and contaminant loading.

XIV. RECOMMENDATIONS FOR SUSTAINABLE GROUNDWATER MANAGEMENT

Based on the integrated assessment, the following measures are recommended:

1. Protection of recharge zones: Natural recharge areas, open spaces, tanks, and drainage corridors should be protected from further urban encroachment.
2. Artificial recharge: Recharge pits, recharge wells, percolation structures, and rainwater harvesting systems should be implemented at suitable locations.
3. Wastewater management: Leakage from sewage networks and septic systems should be identified and eliminated, particularly near groundwater abstraction points.

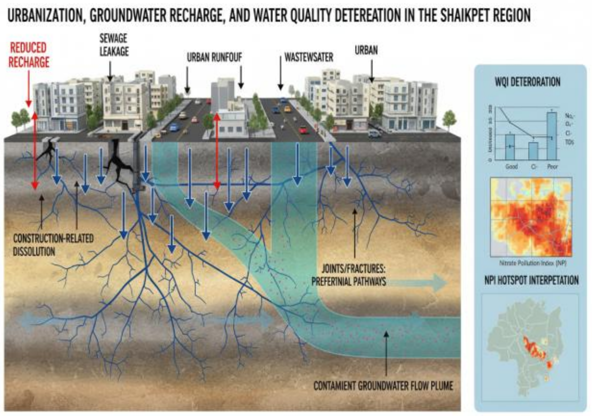

Figure 6: Conceptual 3-D model of urbanization-induced groundwater-quality deterioration in Shaikpet, Hyderabad.

4. Pollution hotspot monitoring: Stations S7, S17, S19, S22, and S23 should receive priority monitoring because of their elevated NPI/WQI values.
5. Urban planning: Future development should incorporate permeable surfaces and stormwater infiltration structures.
6. Groundwater abstraction control: Uncontrolled groundwater extraction should be minimized in areas showing increasing fluoride or dissolved-ion concentrations.
7. Continuous monitoring: Seasonal groundwater monitoring should be conducted to identify long-term changes in EC, TDS, nitrate, chloride, fluoride, and WQI.
8. GIS-based decision support: The RS-GIS database should be periodically updated to monitor urban expansion and identify emerging groundwater-quality hotspots.

XV. CONCEPTUAL MODEL OF URBANIZATION AND GROUNDWATER QUALITY

Figure 6 presents a conceptual three-dimensional model showing the interaction of urbanization, groundwater recharge, hydrogeological conditions, and groundwater-quality deterioration in the Shaikpet region of Hyderabad.
The upper portion of the conceptual model represents the highly urbanized surface environment, where residential buildings, commercial development, institutional infrastructure, roads, and other impervious surfaces dominate the landscape.
The predominance of built-up land in the study region reduces the area available for natural infiltration. Consequently, rainfall that would otherwise contribute to groundwater recharge is increasingly converted into surface runoff.
The figure illustrates three major pathways through which urbanization can affect groundwater quality. First, urban runoff can transport dissolved salts, domestic wastes, and other contaminants toward low-lying areas and recharge locations. Second, leakage from sewage systems, septic tanks, and wastewater disposal sites provides a direct pathway for nitrate, chloride, dissolved solids, and other contaminants to enter the subsurface.
Third, construction activities can enhance the dissolution and mobilization of calcium, magnesium, and other mineral constituents.
The subsurface component represents the weathered and fractured granite aquifer system. The presence of fractures, joints, and weathered zones is important because these structures provide preferential pathways for groundwater movement. Although such zones can enhance groundwater availability and recharge, they can simultaneously facilitate the downward transport of contaminants when polluted surface water enters the subsurface.
The groundwater flow arrows indicate the movement of dissolved contaminants through the aquifer. The conceptual pollution plume represents the cumulative effect of urban-derived contaminants within the groundwater system. This interpretation is consistent with the observed deterioration in groundwater quality at several densely urbanized sampling locations.
The WQI results provide an integrated indication of this deterioration.
In the study dataset, 21 of the 23 stations were classified as Poor, while two stations were classified as Very Poor. The WQI values ranged from 133.89 at S1 to 256.79 at S19 during the reported 2023 assessment. The highest WQI at Valli High School (S19) indicates a location requiring particular attention because of its association with dense urbanization and drainage-related pressures.
The temporal comparison also demonstrates that groundwater deterioration is not spatially uniform. For example, S7 (Saibaba Temple) increased from a WQI of 188.03 in 2022 to 236.33 in 2023, while S19 (Valli High School) increased from 198.47 to 256.79. S18 (Cheruvu Murthy Colony) increased from 194.85 to 210.72, and S23 (The Life Church) increased from 204.77 to 219.24. These changes indicate that locations subjected to increasing wastewater, construction, residential density, and inadequate drainage may experience progressive deterioration.
The Nemerow Pollution Index (NPI) provides additional evidence of contamination severity. High NPI values were reported at S7, S17, S19, S22, and S23. In particular, S7 recorded an NPI of 7.26, S17 recorded 6.03, and S19 recorded 5.94. These values identify these locations as important pollution hotspots requiring targeted investigation and management.
The figure therefore demonstrates that groundwater deterioration in the Shaikpet region should not be attributed to a single contaminant source. Instead, it is the result of the combined influence of rapid land-use conversion, reduced recharge, wastewater leakage, urban runoff, construction activity, groundwater abstraction, and the underlying fractured granite hydrogeological system.

Key Observations Derived from the Conceptual Model Figure-Based Conclusion
The three-dimensional conceptual model demonstrates the coupled relationship between urban land transformation and groundwater-quality deterioration in the Shaikpet region. The model indicates that increasing built-up coverage and impervious surfaces reduce natural recharge while simultaneously increasing runoff and the opportunity for pollutant accumulation.
Sewage leakage, domestic wastewater, construction activities, road runoff, and commercial development provide additional contaminant sources.
The WQI and NPI results strengthen this conceptual interpretation.
The predominance of the Poor WQI class and the occurrence of Very Poor locations demonstrate that groundwater is unsuitable for direct drinking use without

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appropriate treat-ment. The high NPI values at stations such as S7, S17, and S19 further identify localized pollution hotspots.

Table 13: Interpretation of the major components represented in the three-dimensional conceptual groundwater model

Component	Observed Condition	Environmental Interpretation
Urban built-up Area	Approximately 70%	High urban density increases impervious cover and modifies the natural hydrological cycle.
Impervious surfaces	Extensive	Reduced infiltration and increased surface runoff decrease effective groundwater recharge.
Sewage leakage	Important anthropogenic Source	Provides a pathway for nitrate, chloride, dissolved solids, and other contaminants to enter groundwater.
Construction	Increasing urban activity	Can contribute to hardness and dissolved mineral enrichment through cement/material dissolution and subsurface disturbance.
Fractured/weathered granite	Important hydrogeological pathway	Fractures and weathered zones control groundwater movement and can also facilitate contaminant transport.
EC and TDS	Increasing at several locations	Indicate increasing dissolved ionic and mineral loads associated with urban runoff, wastewater infiltration, and groundwater–rock interaction.
Nitrate	Localized high concentrations	Strongly associated with sewage, septic leakage, and domestic wastewater inputs.
Chloride	Elevated at many locations	Useful indicator of wastewater influence and urban runoff.
WQI	Poor to Very Poor	Indicates that most groundwater samples require treatment before drinking.
NPI	High at selected hotspots	Identifies locations requiring focused pollution-control and groundwater management measures.

Therefore, the conceptual model supports the implementation of recharge-zone protection, improved sewage infrastructure, controlled wastewater disposal, rainwater harvesting, artificial recharge structures, and periodic groundwater-quality monitoring.

Particular attention should be given to high-WQI and high-NPI locations because these areas represent the combined effect of intense urban pressure and vulnerable groundwater pathways.

The integrated evidence therefore indicates a coupled relationship between urban land-use change, recharge reduction, contaminant loading, and hydrogeological controls. The approximately 70permeable surfaces and promotes surface runoff, while wastewater leakage, septic discharge, urban drainage, and construction activities provide potential contaminant sources. Fractures and weathered zones within the granitic terrain can then facilitate the movement of recharge water and dissolved contaminants into the aquifer. The resulting groundwater-quality pattern is reflected by the predominance of poor WQI conditions and the occurrence of severe NPI hotspots.

The spatial and temporal results also indicate that groundwater deterioration is heterogeneous rather than uniform across the study area. Locations such as S7, S17, S19, S22, and S23 require greater attention because they combine elevated pollution indicators with intensive urban activity. The increase in WQI observed at several stations between 2022 and 2023 further suggests that groundwater-quality stress may be increasing in selected parts of the study area. However, these temporal changes should be interpreted in conjunction with sampling conditions, seasonal variability, groundwater abstraction, and local hydrogeological characteristics.

Overall, the results demonstrate that groundwater quality in the Shaikpet region is controlled by the combined influence of urbanization, hydrogeology, recharge conditions, and contaminant sources. The findings support the need for protection of remaining permeable and recharge zones, improved wastewater and sewage management, control of uncontrolled discharges, rainwater harvesting, and periodic monitoring of high-risk locations. Priority should be given to stations exhibiting simultaneously high WQI and NPI values, where targeted pollution-control and groundwater management measures are most likely to be beneficial.

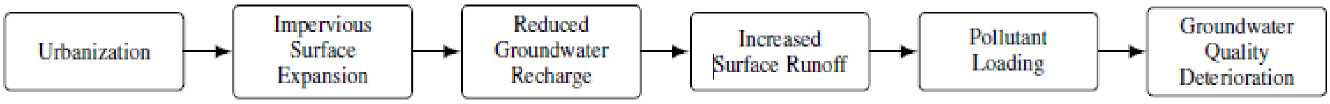

Figure 7: Conceptual flowchart illustrating the influence of urbanization on groundwater quality in the Shaikpet region.

However, this relationship is spatially heterogeneous because groundwater quality is additionally controlled by lithology, fracture density, groundwater-flow direction, drainage characteristics, and local pollution sources. Therefore, urbanization should not be considered the sole determinant of groundwater quality. Instead, the observed groundwater conditions represent the combined influence of anthropogenic pressure and hydrogeological characteristics.
The identification of high-WQI and high-NPI locations provides a basis for prioritizing groundwater-management interventions.
Pollution hotspots such as S7, S17, S19, S22, and S23 should receive priority for detailed source investigation, sewerage inspection, groundwater monitoring, and wastewater management. Recharge structures should preferentially be established in suitable permeable and fractured zones after ensuring that the incoming water is adequately treated. Artificial recharge without appropriate water quality screening may increase contaminant transport and should therefore be avoided near active sewage leakage or contaminated drainage pathways.
Overall, the combined WQI, NPI, physicochemical, and RSGIS findings indicate that the Shaikpet groundwater system is under considerable urbanization pressure. Sustainable groundwater management should therefore integrate land-use planning, protection of recharge zones, improved sewerage infrastructure, reduction of uncontrolled wastewater discharge, artificial recharge at suitable locations, and continuous spatial and temporal groundwater-quality monitoring.

XVI. STUDY LIMITATIONS

The present manuscript is based on the groundwater-quality values and summary statistics supplied for the study. The complete raw analytical dataset for all 23 stations, individual seasonal measurements, exact coordinates, laboratory uncertainty values, and complete LULC imagery classification statistics were not included in the supplied material.
Therefore, the reported results should be interpreted as an integrated assessment based on the available dataset. Before journal submission, the raw laboratory measurements should be cross-checked against the calculated WQI and NPI values, and the exact GIS-derived areas should be reported from the final classified maps.

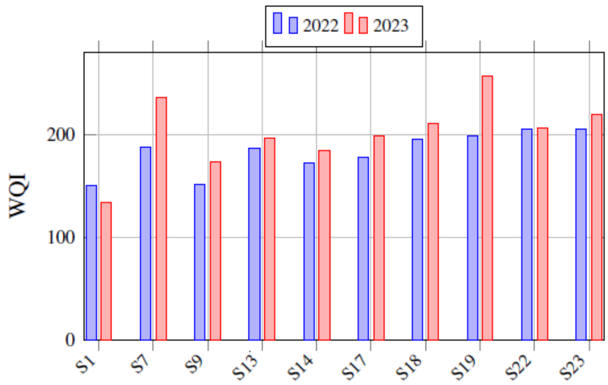

Figure 8: Comparison of WQI values at selected groundwater sampling stations during 2022 and 2023.

XVII. CONCLUSION

The present study demonstrates a clear association between rapid urbanization and groundwater-quality deterioration in the Shaikpet region of Hyderabad. The integration of physicochemical analysis, Water Quality Index (WQI), Nemerow Pollution Index (NPI), Remote Sensing, and GIS provided a comprehensive framework for assessing the spatial and temporal characteristics of groundwater quality.
The LULC analysis indicates that approximately 70occupied by built-up land, resulting in substantial reduction of permeable surfaces and modification of natural groundwater recharge conditions. Although the underlying granitic terrain, fractures, weathered zones, and lineaments influence groundwater occurrence and movement, urban activities appear to exert a strong influence on groundwater-quality conditions.
The WQI assessment indicates that groundwater quality is predominantly poor, with 21 of the 23 sampling stations classified as Poor and two as Very Poor. The highest

reported 2023 WQI value was 256.79 at S19 (Valli High School). Several stations also exhibited increased WQI values between 2022 and 2023, indicating localized deterioration associated with increasing urban and wastewater-related pressures.

The NPI assessment identified S7, S17, S19, S22, and S23 as important pollution-prone locations. The highest reported NPI values were 7.26 at S7 (Saibaba Temple), 6.03 at S17 (Sri Peddamma Talli Temple), and 5.94 at S19 (Valli High School), indicating severe pollution according to the adopted classification.

The major groundwater-quality indicators include EC, TDS, total hardness, calcium, magnesium, nitrate, chloride, sulphate, and fluoride. Elevated concentrations are likely related to the combined effects of wastewater infiltration, sewage leakage, urban runoff, construction activities, mineral dissolution, groundwater–rock interaction, and groundwater abstraction.

The relative contribution of these processes varies spatially according to local land use and hydrogeological conditions. Overall, the findings indicate that groundwater management in Shaikpet requires an integrated approach combining urban planning, protection of remaining recharge zones, improved sewage and wastewater management, rainwater harvesting and artificial recharge, controlled groundwater abstraction, and regular monitoring of identified pollution hotspots. The combined RS–GIS–WQI–NPI framework provides a practical decision-support methodology for identifying vulnerable locations and supporting sustainable groundwater management in rapidly urbanizing regions.

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