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Geospatial technology for the groundwater quality estimation: A review

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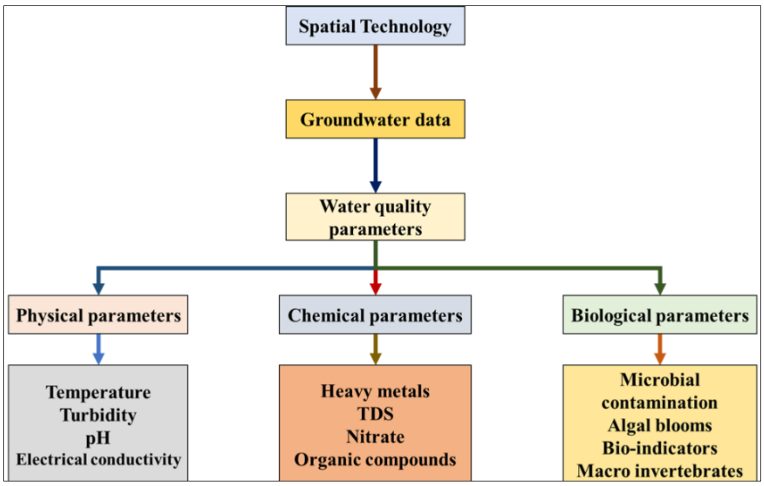
Abstract
Groundwater quality assessment is crucial in the 21st century to ensure sustainable water sources for essential activities. Geospatial technology has emerged as a pivotal tool for accurately estimating groundwater quality. This study reviews the current state of research in this field, emphasizing the potential of geospatial technology to deliver precise and dependable data on groundwater quality. Various techniques within geospatial technology, including remote sensing, geographic information systems (GIS), and spatial interpolation, are explored for their roles in groundwater quality estimation. The study also addresses challenges such as data availability, accuracy issues, and the complexities of data interpretation. By highlighting these aspects, the review underscores the significance of geospatial technology in enhancing our comprehension of groundwater quality and points to opportunities for future research in this critical area.

Graphical abstract



Keywords: Groundwater, quality estimation, Geospatial technology, remote sensing, geographic information systems

Introduction

One of the main issues facing the globe today is access to water resources. The country is majorly ubiquitous about the water scarcity, especially groundwater resource [1, 2]. Due to both natural and man-made factors, over half of the nation is experiencing a catastrophic groundwater issue (basalt rock surface). At the core of the fresh water crisis that jeopardizes global sustainable growth is India, a country that houses around 18% of the world's population and only possesses 4% of the world's fresh water resources [3]. We have seen the water crisis in Cape Town, South Africa, as well as comparable crises in Bengaluru, Chennai, Shimla, Bundelkhand, and a portion of Maharashtra [4]. Approximately two thirds of the world's freshwater resources are made up of groundwater, which is a valuable resource for drinking, agriculture, home use, and industry. For India, the amount and quality of groundwater are major concerns [5, 6].

Because groundwater quality directly affects human health, it is a major problem for humanity. The previous forty years have seen a significant increase in population, making it extremely difficult to provide clean water. Groundwater levels are declining due to a combination of factors including industrialization and other human-caused activities. Highly hazardous pollutants like arsenic, fluoride, nitrate, chloride, fluoride, lead, and heavy metals are contaminating the groundwater [7].

Being a vital component of the planet, groundwater is necessary for ecological health, socioeconomic growth, and human well-being. The demand for fresh water has increased dramatically over the past few decades as a result of the world's fastest-growing population and fastest-paced industrialization [8]. The need to use clean water has gained international attention as a result of the world's population growth, which eventually causes an increase in water demand. In many regions of the world, there is a risk of both quality and quantity degradation with regard to this scarce and delicate resource. The disposal of large amounts of industrial and human waste endangers this priceless resource [9]. Water quality degradation is also a result of excessive pumping and careless aquifer management. Eighty percent of human diseases are caused by water, according to a WHO research. It becomes crucial to control, monitor, and devise methods and means of protecting groundwater since once it is contaminated, its quality cannot be restored by removing the pollutants from their source [10].

In India, there are numerous issues with surface and underground water quality. Many cities across the country are experiencing groundwater contamination as a result of the industries' and urban areas' fast growth [11, 12]. Evaluating the physical, chemical, and biological characteristics of water in connection to its natural quality, human impacts, and intended uses especially those that could have an impact on human health or the health of the aquatic system as a whole is known as water quality assessment [13]. Even though it is crucial to regularly monitor groundwater, it is not always practicable to assess concentration from every place due to the time and expense associated with gathering data [14].

The quality of groundwater is determined by subsurface geochemical processes, atmospheric precipitation, and refreshing water [15]. Periodic changes in water quality indicators can be caused by time-based fluctuations in the source and composition of the recharged water, as well as hydrologic and socioeconomic variables. While naturally occurring physico-chemical parameters like pH, Cl, HCO_3, and TDS can be applied, their effects on irrigation and drinking groundwater suitability may not always be detrimental to health [16, 17]. Elements react below the surface, as do rock miners' effects, weathering, soil, rainfall, dissolution, precipitation, mining areas, and other related processes. Groundwater is considered the most valuable natural resource when it is paired with surface water [18]. Including oceans and perpetual snow, groundwater accounts for around 20% of the world's fresh water resources, or 0.61% of all water on Earth. It is quite concerning when groundwater quality deteriorates as a result of various geogenic and human activities [19, 20].

The chemistry of groundwater varies periodically and is caused by geochemical processes. Furthermore, nutrients and metals may be filtered out of groundwater to produce non-potable water [21]. In the hard rock region, groundwater quality measurements are a major factor in determining which wells are best suited for irrigation and drinking [22]. If the natural baseline quality is strong and confident enough, then the introduction of chemical contaminants and groundwater quality parameter monitoring approaches work well. Pollution effects and the relative contributions of natural sources of variation can both be altered by anthropogenic activity [23].

Hydrochemistry is a crucial subject to understand when evaluating the quality of groundwater in any region where it is utilized for both drinking and irrigation [24]. A variety of factors, including biological, chemical, and physical ones, influence the quality of groundwater. The evaluation of environmental issues, especially groundwater, and natural resource availability has been made much easier by the application of spatial analysis [25]. Groundwater studies are used for solute transport and leaching groundwater flow modelling, groundwater quality assessment models integration with spatial data to create spatial decision support systems using Arc GIS software, site suitability analyses, managing site inventory data, estimation of groundwater vulnerability to contamination, and so on. For the impacted saline zone area, monitoring surface and groundwater quality mapping has become necessary [26, 27]. The characteristics that determine the quality of groundwater are dependent on a variety of factors, including pH, EC, total dissolved solids, Ca, Mg, and nitrate [28].

By analyzing IDW interpolation techniques, water quality maps based on the features of groundwater quality which is based on the identification of desirable well sites were created [29]. Spatial technologies have been used in many earth science-related studies and planning projects. GIS software is useful for mapping the quality of water and is essential for monitoring environmental management and identifying variations. In this review the various water quality parameters which affects on groundwater and the spatial technology for estimation of groundwater quality was discussed.

Methodology

Water quality parameters

Water quality parameters are crucial factors that determine the overall condition of water bodies and their usability for various purposes. Monitoring these parameters is essential for ensuring the safety and health of both humans and aquatic ecosystems [30]. In this report, we will discuss different water quality parameters, their significance, and methods of monitoring them.

Physical Parameters

The physical parameters include temperature, turbidity, color, odor, and clarity of water. Temperature affects the dissolved oxygen levels in water, which in turn affects aquatic life. Turbidity refers to the cloudiness of water due to suspended particles, which can impact light penetration and photosynthesis [31]. Color and odor are indicative of potential contamination, while clarity indicates the presence of sediments. The individual physical parameters were mentioned in the table 1 [32].

Table 1: Physical parameters involves in groundwater quality estimation

Sl. No.	Physical parameters	Description	Ref.
1.	Temperature	The temperature of groundwater can affect various biological processes and chemical reactions within the aquifer.	[33]
2.	Turbidity	Turbidity refers to the cloudiness or haziness of groundwater due to the presence of suspended particles. High turbidity levels can affect water quality and impede filtration processes.	[34]
3.	pH	The pH level of groundwater can influence its acidity or alkalinity, which in turn can impact the solubility of certain minerals and the effectiveness of treatment processes.	[35]
4.	Electrical Conductivity	The concentration of dissolved ions in groundwater affects its electrical conductivity, a measure of its capacity to conduct an electrical current. Elevated conductivity levels could be a sign of pollution.	[36]

Physical parameters include measurements such as temperature, pH level, turbidity, and conductivity. Temperature can affect the solubility of certain chemicals in water, while pH level can indicate the acidity or alkalinity of the water [37]. Turbidity measures the clarity of the water, which can be influenced by suspended particles, and conductivity measures the ability of water to conduct electricity, which can be affected by dissolved solids.

Chemical Parameters

The chemical parameters include pH, dissolved oxygen, nutrients (nitrogen and phosphorus), metals, and organic compounds [38, 39]. pH levels can affect the solubility of chemicals and the effectiveness of biological processes. Dissolved oxygen is essential for aquatic organisms, while excess nutrients can lead to eutrophication and algal blooms [40]. Metals and organic compounds can be toxic to aquatic life and humans. The various chemical parameters of groundwater quality analysis were shown in table 2.

Table 2: Chemical parameters involves in groundwater quality estimation

Sl. No.	Chemical parameters	Description	Ref.
1.	Heavy Metals	Heavy metals such as lead, arsenic, and mercury can contaminate groundwater through industrial activities or natural sources, causing serious health implications.	[41]
2.	Total Dissolved Solids (TDS)	TDS refers to the concentration of dissolved minerals and organic compounds in groundwater, which can affect the taste, odor, and overall quality of water.	[42]
3.	Nitrate	Elevated levels of nitrate in groundwater can result from agricultural runoff or septic system leachate, posing health risks to humans and aquatic organisms.	[43]
4.	Organic Compounds	Organic compounds, including pesticides, solvents, and pharmaceuticals, can leach into groundwater and adversely impact water quality and human health.	[44]

The chemical parameters include concentrations of various pollutants such as heavy metals, nitrates, pesticides, and organic compounds. These pollutants can come from industrial activities, agriculture, and urban runoff [38, 45]. Monitoring methods for chemical parameters typically involve collecting water samples and analyzing them using laboratory techniques such as spectroscopy and chromatography [46].

Biological Parameters

The biological parameters involve the presence of indicator organisms such as coliform bacteria, algae, and macroinvertebrates [47, 48]. Coliform bacteria are indicators of fecal contamination, while algae can indicate nutrient enrichment. Macroinvertebrates serve as bioindicators of water quality and habitat integrity [49]. The various biological parameters of groundwater quality analysis were shown in table 3.

Table 3: Biological parameters involves in groundwater quality estimation

Sl. No.	Biological parameters	Description	Ref.
1.	Microbial Contamination	Bacteria, viruses, and parasites can contaminate groundwater sources, leading to waterborne diseases if consumed.	[50]
2.	Algal Blooms	Excessive levels of nutrients in groundwater can promote the growth of algae, forming toxic algal blooms that can harm aquatic habitats and water quality.	[51]
3.	Macroinvertebrates	The presence of certain macroinvertebrates in groundwater can indicate ecological health, as these organisms play vital roles in nutrient cycling and food webs.	[52]
4.	Bioindicators	Bioindicators, such as certain species of plants or microbes, can be used to assess the overall biological health and integrity of groundwater ecosystems.	[53]

The biological parameters refer to the presence of microorganisms in the water, including bacteria, viruses, and parasites [17]. These organisms can indicate potential contamination and health risks. Monitoring methods for biological parameters may involve testing for indicators such as coliform bacteria or measuring biological oxygen demand (BOD) to assess the level of organic matter in the water [54].

Monitoring Methods

Monitoring water quality parameters can be done through various methods, including field testing kits, laboratory analysis, and remote sensing technologies [55, 56]. Field testing kits provide rapid results for basic parameters like pH, dissolved oxygen, and turbidity. Laboratory analysis offers more detailed information on chemical and biological parameters. Remote sensing technologies use satellite imagery to monitor large water bodies and track changes over time [57].

Spatial mapping in groundwater quality analysis

Groundwater quality analysis plays a critical role in maintaining the sustainability of water resources. Spatial mapping is a valuable tool in groundwater quality analysis as it allows for the visualization of variations in water quality across a geographical area. This report outlines the procedure for conducting spatial mapping in groundwater quality analysis. Spatial mapping technology is a powerful tool used in water quality mapping to gather and analyze data related to various water parameters such as pH levels, dissolved oxygen, turbidity, and nutrient concentrations [58]. This technology allows researchers and environmental scientists to create detailed maps that show the distribution of water quality across a specific area, helping them to identify sources of pollution and plan for remediation efforts. Procedure of spatial technology in water quality mapping [59, 60]. The researchers begin by collecting water samples from various points in a water body, using specialized equipment to measure different water quality parameters. These data points are then geotagged using GPS technology to ensure accuracy in spatial mapping. The collected data is input into Geographic Information Systems (GIS) software, which allows researchers to create visually detailed maps showing the distribution of water quality parameters across the study area [61]. GIS software also enables the overlay of different data layers, such as land use patterns and water flow, to better understand the relationship between water quality and surrounding factors. The researchers analyze the mapped data to identify patterns and trends in water quality, such as areas of high pollution or contamination [62]. This information can help them pinpoint specific sources of pollution and prioritize areas for conservation and management efforts. The mapped data and analysis results are compiled into a comprehensive report that can be shared with stakeholders, policymakers, and the public [28, 63]. This report can be used to guide decision-making processes related to water quality management, conservation, and restoration efforts. The spatial mapping procedure was explained in the table 4.

Table 4: Spatial mapping procedure for groundwater quality estimation

Sl. No.	Steps	Description
1.	Sampling Design	▪ Determine the area of interest for groundwater quality analysis. ▪ Establish sampling points in a grid pattern to cover the entire area uniformly. ▪ Ensure that the sampling points are representative of the variability in groundwater quality.
2.	Field Sampling	▪ Collect water samples from each sampling point using a clean, sterile container. ▪ Record the location, date, and time of sampling for each sample. ▪ Measure in-situ parameters such as pH, temperature, conductivity, and dissolved oxygen at each sampling point.
3.	Laboratory Analysis	▪ Transport the water samples to a certified laboratory for analysis. ▪ Conduct tests for physical and chemical parameters, including turbidity, total dissolved solids, major ions (e.g., calcium, magnesium, sodium, chloride), heavy metals, and organic pollutants (e.g., pesticides, herbicides). ▪ Ensure that the laboratory follows standard protocols for water quality analysis.
4.	Data Analysis	▪ Input the analytical results into a GIS software for spatial mapping. ▪ Create thematic maps of each water quality parameter to show spatial variations. ▪ Perform statistical analysis to identify trends and correlations in the data.
5.	Interpretation and Reporting	▪ Analyze the spatial maps to identify areas of concern or hotspots of pollution. ▪ Generate a report summarizing the findings of the groundwater quality analysis. ▪ Provide recommendations for remediation or mitigation measures based on the spatial mapping results.

In general, geospatial technology is the most appropriate for examining spatial variations in water quality, as it is a more efficient approach to groundwater management. The city government will benefit from the themed maps of groundwater quality criteria for efficient groundwater management and monitoring. To assess the variation in results, other geostatistical techniques (IDW, EBK) might be taken into consideration.

Challenges in geospatial technology for groundwater quality estimation

Geospatial technology plays a crucial role in groundwater quality estimation, allowing researchers to analyze and visualize data in a spatial context. However, there are several challenges that can hinder the accuracy and reliability of groundwater quality estimation using geospatial technology. One of the main challenges is the lack of high-quality and up-to-date spatial data. Groundwater quality can vary significantly over time and space, and without accurate and current data on factors such as land use, geology, and hydrology, it can be difficult to accurately estimate groundwater quality [64]. In many cases, data may be outdated or insufficient, leading to inaccuracies in the estimation of groundwater quality. Another challenge is the complexity of the interactions between different factors that affect groundwater quality. Groundwater quality can be influenced by a wide range of factors, including land use practices, water extraction activities, and natural geological processes [65, 66]. Integrating all of these factors into a geospatial model can be challenging, and there is a risk of oversimplifying or overlooking important interactions that Geospatial technology has revolutionized how we analyze and understand our planet's landscapes and resources. In the realm of groundwater quality estimation, however, there are several challenges that professionals in the field must overcome in order to accurately assess and manage this vital resource [67].

One of the main challenges in using geospatial technology for groundwater quality estimation is the lack of reliable and up-to-date data. Groundwater quality can vary significantly based on a wide range of factors, including land use, geology, and industrial activities [68]. In order to accurately estimate groundwater quality, professionals need access to comprehensive and current data from a variety of sources. This can be a significant challenge, as data collection and analysis can be time-consuming and costly [69]. Another challenge in using geospatial technology for groundwater quality estimation is the complexity of the modeling process. Groundwater systems are inherently complex and dynamic, with a wide range of variables that can impact water quality. Creating accurate and reliable models that can account for all of these variables can be a daunting task, requiring advanced technical expertise and specialized software tools [70, 71].

Furthermore, the interpretation of geospatial data in the context of groundwater quality estimation can be challenging due to the inherent uncertainties and limitations of the data itself. Geospatial datasets are often subject to errors and inaccuracies, which can impact the accuracy of groundwater quality estimates [72]. Additionally, interpreting geospatial data requires a deep understanding of geology, hydrology, and other related disciplines, making it a specialized and complex task while geospatial technology holds great potential for improving our understanding of groundwater quality, there are several challenges that must be addressed in order to effectively utilize this technology in the field [73, 74]. By addressing issues such as data reliability, modeling complexity, and data interpretation, professionals can overcome these challenges and improve our ability to accurately estimate and manage groundwater quality.

Conclusion

Water quality parameters play a crucial role in determining the health and usability of water bodies. Monitoring these parameters is essential for maintaining water quality standards and protecting human health and aquatic ecosystems. By utilizing a combination of physical, chemical, and biological parameters, we can ensure the sustainability of our water resources for future generations. The use of spatial technology in water quality mapping provides valuable insights into the health of our water bodies and informs conservation and management strategies that aim to protect and preserve these vital resources. geospatial technology has proven to be a valuable tool for accurately measuring and monitoring groundwater quality. By using advanced mapping and data analysis techniques, researchers and environmental professionals can gain valuable insights into the distribution and movement of contaminants in groundwater systems. This information is crucial for making informed decisions regarding water resource management and conservation efforts. Overall, geospatial technology has greatly enhanced our ability to protect and preserve groundwater quality for both current and future generations.

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