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Exploring the Hydrochemical Properties of Groundwater in Madurai District for Sustainable Water Management

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Abstract
Groundwater is one of the most critical water resources on earth and it is a significant source of water for domestic consumption, agriculture and industry. Its reliability makes it invaluable, especially where there is a lack of surface water or seasonally varying surface water. In Madurai District, groundwater has been a lifeline to generations, supporting local communities and agricultural systems. Sadly, the present status of groundwater in Madurai is a cause for concern in terms of quantity and quality. Excessive extraction over the past decades has resulted in a noticeable reduction in groundwater levels in Madurai. Coupled with this, uncontrolled waste disposal, agricultural runoff and industrial effluent has dumped pollutants into the aquifers. Recent hydro-chemical investigations indicate high salinity, hardness and nitrates in some areas, which indicates that pollution is exerting a negative effect on water quality. Such changes undermine not only human health but also the long-term sustainability of agricultural production in the district. Resolution of these issues involves the adoption of sustainable water management practices appropriate to the particular context of Madurai District. Implementing best practices for groundwater management is essential for sustainable water resources. This involves promoting recharge initiatives to replenish aquifers, limiting water withdrawal to prevent over-extraction and establishing comprehensive monitoring systems to assess both water quantity and quality. Utilizing advanced hydro-chemical analysis and spatial mapping techniques, pollution hotspots can be accurately identified, allowing for targeted remediation efforts. These measures collectively contribute to maintaining a balanced groundwater supply, ensuring safe and reliable water for domestic, agricultural, and industrial needs.

Keywords: *Hydro-chemical Analysis, Sustainable water resource, Water Quality*

1. Introduction

Groundwater is a vital source of freshwater for drinking, agriculture, and industrial use. It is particularly crucial in areas where the availability of surface water is not adequate or stable. Groundwater quality also determines its usability; hence its assessment is essential to ensure efficient and sustainable management of the water resource. Protection of groundwater quality is essential to ensure ecological balance and public health. The growing population, along with fast urbanization and industrial development, has caused tremendous pressure on groundwater resources, and hence its chemical composition and safety for use have become issues of concern. India, being a nation that is highly reliant on groundwater for various sectors, is facing various challenges because of uncontrolled abstraction, contamination, and climatic fluctuations. Madurai District in the southern Tamil Nadu is dependent to a great extent on groundwater for drinking and irrigation. Several natural and man-made factors influence the hydrochemical characteristics of the groundwater in the area. They are geological formations, climatic pattern variations, excessive groundwater drawdown, movement of contaminants by agricultural runoff, and industrial effluents. These influences lead to the deterioration of water quality, and hence it is important to study its suitability for different purposes and formulate measures to counteract possible problems. Hydro-chemical study is important in determining groundwater quality by studying different physical and chemical parameters. These include the determination of pH, electrical conductivity, total dissolved solids (TDS), and major ionic contents like calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate. Also, trace elements and heavy metals need to be evaluated to identify contamination levels and health hazards. The purpose of this study is to extensively examine the hydrochemical properties of groundwater in Madurai District, identifying current water quality issues and recommending sustainable management practices. The study utilizes statistical equipment to analyze the data that is gathered, allowing for the observation of trends and association among various hydrochemical parameters. Through the observation of trends, this research aims to give useful information on groundwater preservation, prevention of contamination, and sustainably using the resources. The results from this study will inform policies and regulations that favor the protection of groundwater while ensuring long-term sustainability. Furthermore, the combination of hydrochemical analysis with statistical approaches improves the accuracy and reliability of groundwater quality estimation. This integrative approach will help policymakers, environmental agencies, and local societies make informed groundwater management decisions. Finally, the research hopes to contribute to sustainable groundwater resource use, making sure that the resource is available to future generations without compromising on today's water contamination and over-pumping issues. Based on a well-organized and scientific methodology, this study highlights the need for sustainable groundwater exploitation in Madurai District and presents solutions, which can be tailored to be applicable for similar areas with water quality issues. Groundwater chemistry is important not only to evaluate its present status but also to project future water quality changes. Climate change, changes in land use, and growing water demand are all contributing factors to modifying the hydro-chemical nature of groundwater over the years. Through the inclusion of long-term monitoring and predictive modeling methods, this study will establish an integrative framework for groundwater management that is responsive to changing environmental and anthropogenic stresses. In addition, the research will investigate possible remedial actions, including artificial recharge methods, control of pollution measures, and ecological farming practices, to enhance the quality of groundwater and make it usable in the long term. Public education and community involvement also have an important role to play in groundwater preservation, and the research will focus on the necessity of joint collaboration between government institutions, researchers, and local stakeholders to ensure efficient water resource management. The findings of this research will act as a valuable tool for further research, assisting in filling the knowledge gaps within hydro-chemical analysis and its role in sustainable water management. By utilizing scientific research and policy action, this research hopes to contribute significantly towards the overall aim of providing safe and adequate groundwater to current and future generations [1-5].

2. Groundwater Importance

Groundwater is an essential natural resource sustaining domestic, agricultural, and industrial use in Madurai District. Due to rising population growth and urbanization, the requirement for groundwater has also increased enormously, necessitating its conservation and sustainable management. Since surface water sources are still limited owing to climatic fluctuations and seasonal dependence on rainfall, groundwater is a reliable alternative to satisfy the needs of the region. Hydrochemical investigations are of utmost importance in determining the viability of groundwater for drinking and irrigation. Physicochemical examination of groundwater yields vital information about water quality to ascertain safe use for different purposes. [karthik] In places such as Madurai, where groundwater is a major drinking water and irrigation source, continuous monitoring of its hydrochemical characteristics is vital to avoid contamination and degradation. The several natural and manmade sources like geological formations, industrial effluent discharge, agricultural runoff, and

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over-exploitation drive the groundwater quality in the region. Classification and evaluation of groundwater quality based on hydrochemical analysis give useful input on water usability. Groundwater chemistry is identified and understood by determining its classification and possible constraints for use. The research points out that the parameters of pH, electrical conductivity, total dissolved solids (TDS), and major ions have a great influence on the usability of groundwater [Basavaraddi]. Likewise, in Madurai District, these parameters are of prime importance in determining the sustainability of groundwater resources, especially for agricultural use, since high salinity and ion concentration can influence soil fertility and crop yield. The increasing threat of groundwater depletion and pollution in Madurai calls for the establishment of efficient management practices. Controlled extraction, artificial recharge methods, and pollution prevention measures are all necessary for the long-term water security of sustainable groundwater management practices. Through the combination of hydrochemical analysis and conservation, authorities and stakeholders can formulate policies that ensure the sustainable utilization of groundwater resources. In general, groundwater is a key component of water security in Madurai District. Under growing anthropogenic pressures, systematic hydrochemical evaluation and sustainable management strategies are essential to protect groundwater quality and quantity for future generations [6-9].

3. Groundwater Contamination

Groundwater Contamination in Madurai District
Groundwater contamination is a growing concern in Madurai District due to rapid urbanization, industrial expansion, and intensive agricultural activities. As groundwater serves as the primary source of drinking water and irrigation, maintaining its quality is crucial for public health and environmental sustainability. Various natural and anthropogenic factors contribute to the deterioration of groundwater quality, making regular monitoring and management essential [10-14].

3.1. Sources of Groundwater Contamination

- Industrial and Domestic Wastewater Unregulated discharge of industrial effluents and untreated domestic sewage into open lands and water bodies has significantly impacted groundwater quality in Madurai. [n1].Heavy metals, toxic chemicals, and organic pollutants seep into aquifers, leading to contamination that poses serious health risks.
- Agricultural surface water Runoff The extensive use of chemical fertilizers and pesticides in agricultural fields leads to the infiltration of nitrates, phosphates, and other harmful substances into groundwater. High nitrate concentrations, often linked to excessive fertilizer application, can cause serious health issues such as methemoglobinemia (blue baby syndrome).
- Over-Extraction and Saline Water Intrusion Excessive groundwater extraction for domestic and agricultural use has resulted in a decline in water tables, leading to the intrusion of saline water in certain areas. Increased salinity affects the potability of water and reduces agricultural productivity.
- Geogenic Contaminants Naturally occurring contaminants such as fluoride, arsenic, and iron are present in some groundwater sources in Madurai due to local geological formations. Long-term exposure to high fluoride levels can lead to dental and skeletal fluorosis, affecting the health of the local population [15-19], shown in Figure 1.

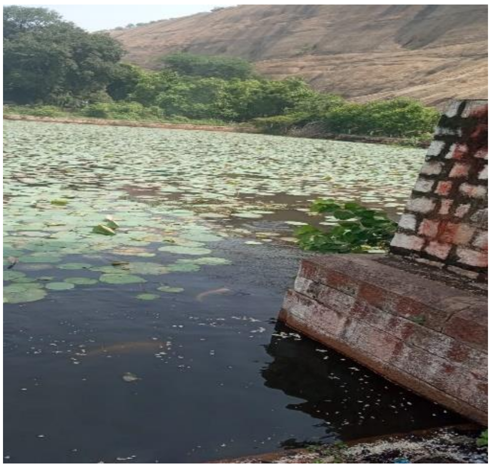

Figure 1 Groundwater Contamination

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3.2. Effects of Groundwater Contamination

- Health Impacts: Contaminated groundwater, if consumed without proper treatment, can lead to various health issues, including gastrointestinal diseases, kidney disorders, and neurological problems.
- Agricultural Decline: Poor groundwater quality affects soil fertility, reducing crop yields and threatening food security in the region.
- Ecosystem Degradation: Contaminants leaching into groundwater can also affect nearby surface water bodies, disrupting aquatic ecosystems and biodiversity [n2]

3.3. Mitigation and Management Strategies. To address Groundwater Contamination in Madurai District, the Following Strategies are Recommended:

- Regular Groundwater Monitoring: Implementing systematic water quality assessments to identify contamination sources and trends [20-24].
- Wastewater Treatment: Strengthening wastewater treatment infrastructure to prevent industrial and domestic effluents from polluting groundwater.
- Sustainable Agricultural Practices: Encouraging the use of organic fertilizers and precision farming techniques to reduce chemical runoff.
- Artificial Recharge Techniques: Promoting rainwater harvesting and managed aquifer recharge to restore groundwater levels and improve water quality.
- Public Awareness and Policy Implementation: Educating local communities on groundwater conservation and enforcing stricter regulations on pollution control.

Water samples used for estimating the of physical properties and chemical properties via., SO4, NO3, metals and DO, COD, BOD and PO4 were collected in plastic bottles and specialized glasswares respectively[m1]. By adopting these measures, groundwater contamination in Madurai District can be effectively controlled, ensuring a sustainable and safe water supply for future generations [25-29].

4. Physical Parameteres

- **Temperature:** Groundwater temperature is often stable, but can vary depending on depth, season, and proximity to surface water bodies. This parameter affects the solubility of gases like oxygen and can influence biological activities [30].
- **Turbidity:** This measures the cloudiness of water caused by suspended solids. Higher turbidity can indicate contamination or high levels of suspended particles, which may affect the filtration process and water quality.[n3]
- **Color:** The natural color of groundwater can indicate the presence of organic material or dissolved minerals. Excessive color can sometimes be associated with high levels of iron, manganese, or organic compounds.
- **Electrical Conductivity (EC):** EC is used as a proxy for TDS because it measures the ability of water to conduct electricity, which increases with higher concentrations of dissolved ions. It helps in assessing water suitability for irrigation.
- **Odour**: Unpleasant odors in groundwater could indicate contamination from organic matter, sewage, or industrial pollutants.[n3]

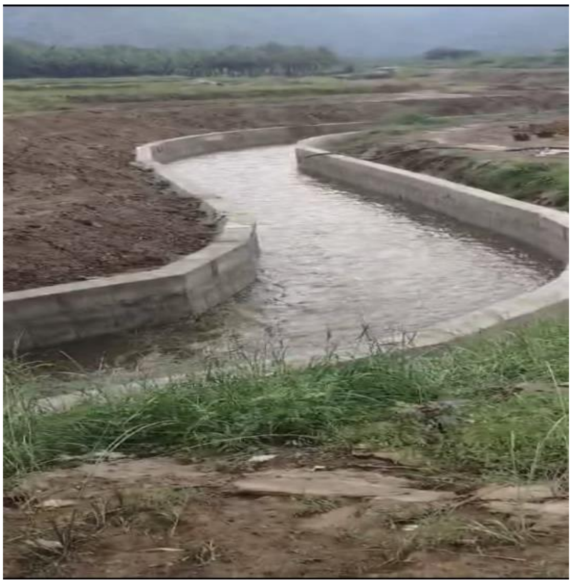

Figure 2 The Way

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4.1. Importance

Physical parameters of groundwater, such as temperature, turbidity, color, total dissolved solids (TDS), electrical conductivity (EC), odor, and pH, play a crucial role in determining water quality and its suitability for various uses. These parameters provide vital insights into the chemical composition, biological activity, and overall health of groundwater resources. Temperature influences the solubility of gases and microbial activity, while turbidity and color can indicate contamination or the presence of suspended particles. TDS and EC are important indicators of the mineral content, which directly affects the taste, health risks, and suitability for irrigation. pH levels help assess the water's corrosiveness and its compatibility with different applications. Additionally, an abnormal odor may point to contamination from organic or industrial sources. Monitoring these parameters helps in managing groundwater effectively, ensuring safe drinking water, and preventing potential health risks or environmental damage [31-34].

4.2. Analysis

Analyzing the physical parameters of groundwater is essential for assessing water quality and determining its suitability for consumption, irrigation, and industrial use. By measuring parameters like temperature, turbidity, color, total dissolved solids (TDS), electrical conductivity (EC), pH, and odor, it is possible to gain insights into the presence of contaminants, mineral composition, and overall water health. [n4].For instance, high turbidity or unusual color may suggest pollution or the presence of organic matter, while elevated TDS or EC levels could indicate the presence of salts or minerals, which might affect the water's taste or make it unsuitable for irrigation. The pH level is a key factor in understanding water's corrosiveness, its effect on agricultural soil, and its compatibility with infrastructure. Regular analysis of these parameters helps identify potential problems, such as contamination or degradation, allowing for appropriate remediation measures to ensure the safe and sustainable use of groundwater resources. This analysis is vital for managing water resources, especially in regions like Madurai, where groundwater is crucial for agriculture and daily consumption [35-39].

5. Chemical Parameters

The chemical parameters of groundwater provide crucial information about its quality and its suitability for drinking, irrigation, and industrial use. Here are some key chemical parameters along with their acceptable limits:

1. **pH**
   - Limit: 6.5 to 8.5 (WHO standards)
   - Importance: pH measures the acidity or alkalinity of groundwater. Water with a pH below 6.5 is considered acidic, which may cause corrosion of pipes, while pH above 8.5 is considered alkaline and may lead to scaling in pipes and affect plant growth.
2. **Total Dissolved Solids (TDS)**
   - Limit: 500 mg/L (Desirable limit for drinking water) and up to 2000 mg/L (Acceptable limit) (WHO standards)
   - Importance: TDS represents the concentration of dissolved salts, minerals, and metals in the water. High TDS levels can affect taste and may lead to health issues or unsuitability for irrigation.
3. **Hardness**
   - Limit: 300 mg/L (WHO guidelines for drinking water)
   - Importance: Hardness is caused by dissolved calcium and magnesium salts. Water with high hardness can lead to scaling in pipes and household appliances, and it can affect soap efficiency.
4. **Chloride (Cl^-)**
   - Limit: 250 mg/L (WHO guidelines)
   - Importance: Chlorides in groundwater are primarily due to the presence of salts. Excessive chloride levels can affect the taste and corrosiveness of water and may damage plant life if used for irrigation.
5. **Sulfate (SO_4^{2-})**
   - Limit: 250 mg/L (WHO standards)
   - Importance: Sulfates can be harmful if consumed in large quantities, leading to a laxative effect. High sulfate concentrations can also cause water to have a bitter taste.

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6. **Nitrate (NO_3^-)**
- Limit: 50 mg/L (WHO guidelines for drinking water)
- Importance: Nitrate contamination is primarily caused by fertilizers and sewage. Excessive nitrate concentrations in drinking water can cause methemoglobinemia (blue baby syndrome) in infants.

7. **Iron (Fe)**
- Limit: 0.3 mg/L (WHO guidelines)
- Importance: High iron concentrations in groundwater can lead to staining of laundry, plumbing, and utensils. It can also affect the taste of water and may be an indication of contamination.

8. **Fluoride (F^-)**
- Limit: 1.5 mg/L (WHO guidelines)
- Importance: Fluoride in groundwater can be beneficial for dental health at low levels (0.5–1 mg/L) but can lead to dental or skeletal fluorosis when concentrations exceed the safe limit.

9. **Ammonia (NH_3)**
- Limit: 0.5 mg/L (WHO guidelines)
- Importance: Ammonia contamination often arises from sewage or agricultural runoff. High concentrations can indicate pollution and can be toxic to aquatic life.

10. **Phosphate (PO_4^{3-})**
- Limit: 0.1 mg/L (General guideline)
- Importance: Phosphates can contribute to eutrophication in water bodies and are commonly associated with agricultural runoff. Elevated levels can promote the growth of harmful algae.

11. **Calcium (Ca^{2+})**
- Limit: 75 mg/L (Desirable limit for drinking water)
- Importance: Calcium contributes to the hardness of water. High concentrations can lead to scaling in plumbing and appliances, but it is essential for human health in moderate amounts.

12. **Magnesium (Mg^{2+})**
- Limit: 30 mg/L (Desirable limit for drinking water)
- Importance: Magnesium, like calcium, contributes to water hardness. It is important for human health but can cause problems like scaling if present in high amounts.

Regular testing of these chemical parameters helps in assessing the quality of groundwater and determining its safety for consumption, agriculture, and industrial use. If the values exceed the recommended limits, appropriate treatment methods must be employed to ensure the water is safe for use [40].

5.1. Importance

Chemical parameters of groundwater are essential for understanding its quality, health implications, and suitability for various uses, including drinking, irrigation, and industrial processes. These parameters offer insights into the composition of dissolved substances, including minerals, salts, gases, and organic compounds, that influence the water’s safety and effectiveness. For instance, pH levels help assess the water's acidity or alkalinity, which impacts its corrosiveness and suitability for plants, infrastructure, and industrial equipment. [n5]. Total dissolved solids (TDS) and electrical conductivity (EC) are indicators of salinity and mineral content, which affect water taste, soil quality for agriculture, and potential risks of water salinization. High levels of nitrates and ammonia may suggest contamination from agricultural runoff or sewage, posing health risks, especially to infants. Hardness, caused by calcium and magnesium, affects water's suitability for domestic use and can lead to scaling in pipes and appliances. Other parameters like chlorides and sulfates impact water’s taste and corrosiveness, while fluoride concentrations must be carefully monitored to prevent dental or skeletal fluorosis. Iron can affect water color, taste, and plumbing, and high concentrations of phosphates can contribute to eutrophication in aquatic environments, leading to ecosystem damage. In summary, the chemical parameters of groundwater are crucial for maintaining public health, ensuring safe drinking water, optimizing agricultural practices, and preventing damage to infrastructure. Monitoring these parameters helps in early detection of pollution and provides a basis for water treatment and management strategies [41-44].

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5.2. Analysis

The analysis of chemical parameters in groundwater within Madurai District provides important insights into the water quality and its suitability for various uses like drinking, agriculture, and industry. Groundwater in Madurai, like in many other regions, can be influenced by both natural processes and anthropogenic activities, making the chemical parameter analysis crucial for sustainable water management. Here's an analysis of the key chemical parameters in the groundwater of Madurai District:

1. **pH Levels**: The groundwater in Madurai generally has a slightly alkaline pH, often ranging from 7.0 to 8.5. This is typical of groundwater from regions with limestone and basalt formations. The pH of the groundwater can influence its suitability for irrigation, as highly alkaline water can affect soil health, particularly affecting the availability of nutrients for plants.
2. **Total Dissolved Solids (TDS)**: Groundwater in Madurai District tends to have moderate to high TDS levels, often ranging from 500 to 1500 mg/L, depending on the location. Elevated TDS concentrations are generally due to the presence of minerals like calcium, magnesium, and sodium. High TDS levels can affect water taste and may reduce its suitability for both drinking and irrigation, as excessive salts can harm soil fertility.
3. **Hardness**: Groundwater hardness in Madurai is typically high, especially in areas with significant limestone deposits. Hardness levels of 300 mg/L or more are common, largely due to dissolved calcium and magnesium. While hard water isn't a health risk, it can cause scaling in pipes, household appliances, and irrigation systems. The high hardness in groundwater can also reduce the efficiency of soaps and detergents.
4. **Chlorides**: Chloride concentrations in groundwater in Madurai often range from 20 mg/L to 250 mg/L. Elevated chloride levels, especially those approaching the higher end of the range, can affect the water's taste and may be indicative of pollution sources such as sewage or industrial waste.[n6] Excess chloride can also lead to corrosion of infrastructure and impact soil salinity if used for irrigation.
5. **Nitrates**: Nitrate contamination is a concern in agricultural regions, and Madurai is no exception. Nitrate levels often exceed the safe drinking water limit of 50 mg/L, especially in areas with intensive agricultural activity using chemical fertilizers. High nitrate concentrations can be harmful to infants, causing methemoglobinemia (blue baby syndrome). Monitoring nitrate levels is critical to prevent contamination from agricultural runoff and ensure water safety for consumption.[n7]
6. **Iron (Fe)**: Elevated iron concentrations are commonly found in groundwater in Madurai, with levels often exceeding 0.3 mg/L, the acceptable limit for drinking water. The presence of iron can give the water a reddish-brown color and affect its taste, while also staining clothes and plumbing. [n7]The source of iron is typically from natural mineral deposits in the groundwater.
7. **Fluoride (F^-)**: Fluoride levels in the groundwater of Madurai District can vary, with some areas showing concentrations that exceed the permissible limit of 1.5 mg/L. High fluoride concentrations, particularly in rural areas, can lead to dental and skeletal fluorosis, which is a significant health concern. In contrast, low levels of fluoride may offer benefits for dental health, but managing fluoride concentrations is crucial for health safety.
8. **Sulfates (SO_4^{2-})**: Sulfate concentrations in groundwater in Madurai typically range between 100 and 300 mg/L. High sulfate levels, often a result of both natural mineral deposits and pollution from industrial activities, can affect the taste of water and cause a laxative effect if consumed in large quantities. Sulfates also contribute to corrosion in pipes and water infrastructure.

9. **Ammonia (NH_3)**: Ammonia concentrations in Madurai's groundwater are usually low, but elevated levels can sometimes be detected in areas with poor sanitation or agricultural runoff. Ammonia contamination can lead to toxicity, especially in aquaculture and irrigation, and indicate the presence of organic pollution.
10. **Phosphate (PO_4^{3-})**: Phosphate levels in groundwater are generally low in Madurai, but agricultural activities that use fertilizers can occasionally lead to increased phosphate concentrations. Phosphates can contribute to eutrophication in surface water bodies, promoting excessive algae growth and degrading water quality.

5.3. Biological Parameters

Biological parameters in groundwater refer to the presence and concentration of microorganisms that can affect the water quality and its suitability for consumption, agriculture, and other uses. These parameters are crucial for understanding potential health risks, as certain microorganisms can lead to waterborne diseases. The primary biological parameters commonly analyzed in groundwater include:

1. **Coliform Bacteria:**
   - **Importance:** Coliform bacteria are used as indicators of fecal contamination in water. The presence of coliforms, especially fecal coliforms, suggests that harmful pathogens may be present, including bacteria, viruses, and parasites. Their presence is a red flag for poor sanitation and pollution from agricultural runoff or sewage.
   - **Limit:** Groundwater should ideally be free from coliform bacteria. A safe drinking water standard is 0 CFU/100 mL (colony-forming units).
2. **E. coli (Escherichia coli):**
   - **Importance:** E. coli is a specific type of fecal coliform and is a direct indicator of recent contamination from human or animal feces. Its presence indicates a high likelihood of waterborne diseases like cholera, dysentery, and gastroenteritis.
   - **Limit:** Like coliforms, groundwater should ideally be free from E. coli. A concentration of 0 CFU/100 mL is recommended for drinking water.
3. **Total Bacterial Count:**
   - **Importance:** This parameter measures the total number of bacteria present in water, which includes both harmful and non-harmful species. High bacterial counts can indicate contamination from organic matter, poor storage conditions, or inadequate filtration.
   - **Limit:** A high total bacterial count in drinking water is typically above 100 CFU/100 mL, which indicates contamination and requires treatment.
4. **Fecal Streptococci:**
   - **Importance:** These bacteria are also used as indicators of fecal contamination. Fecal streptococci are more resistant to environmental conditions than coliform bacteria, and their presence in groundwater may indicate contamination by animal waste.
   - **Limit:** Like coliforms and E. coli, fecal streptococci should ideally be absent from drinking water.
5. **Enterococci:**
   - **Importance:** Enterococci are bacteria found in the intestines of warm-blooded animals, and their presence is used to assess fecal contamination. They are more resistant to environmental conditions than E. coli and are therefore more useful in monitoring the effectiveness of water disinfection.
   - **Limit:** Drinking water should have no detectable enterococci. A concentration of 0 CFU/100 mL is recommended.
6. **Protozoa:**
   - **Importance:** Protozoa, such as Giardia and Cryptosporidium, are microscopic parasites that can cause gastrointestinal illness if consumed through contaminated water. These organisms are often found in surface water, but they can also be present in groundwater, particularly in areas with poor

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sanitation.

- **Limit:** Groundwater should be free from protozoa, as their presence indicates contamination and potential health risks.

7. **Viruses:**

- **Importance:** Waterborne viruses, such as rotavirus and enteric viruses, are another concern in contaminated groundwater. These viruses can cause severe illnesses and are typically transmitted through fecal contamination.
- **Limit:** Groundwater should ideally be free of viruses. Testing for viruses can be complex, but their presence can indicate a high risk of waterborne diseases.

8. **Algae:**

- Algal blooms can produce toxins that contaminate water and pose health risks when consumed.
- Limit: Groundwater should have minimal algae growth. Algal presence is typically a sign of contamination or poor water quality.

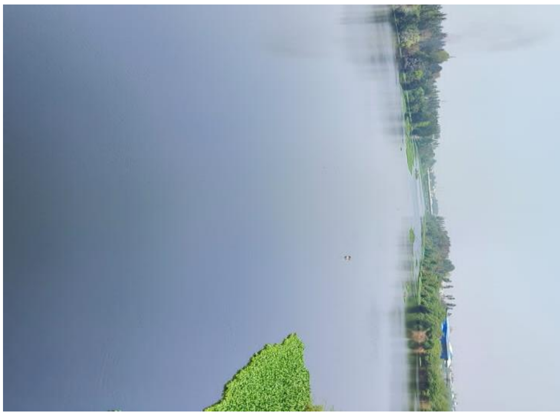

Figure 3 Biological Parameters

The Figure 2 biological parameters of groundwater play a crucial role in assessing its safety for consumption. The presence of microorganisms like coliforms, E. coli, and other pathogens indicates fecal contamination, which can pose serious health risks. Regular monitoring of biological parameters is essential for ensuring that groundwater remains free from harmful organisms and safe for drinking, agricultural, and industrial use. Treatment options such as filtration, chlorination, UV treatment, and reverse osmosis are often required to remove harmful biological contaminants from groundwater.

5.4. Analysis

The biological parameters of groundwater refer to the presence of microorganisms such as bacteria, viruses, protozoa, and algae, which can affect water quality and pose health risks. [n8] Biological contamination is a key concern for groundwater, particularly for drinking water supplies, as it can lead to waterborne diseases. The biological testing of groundwater helps determine the presence and concentration of these microorganisms, ensuring the water is safe for human consumption, irrigation, and other uses.

Here's a broad explanation of the common biological parameters tested in groundwater:

1. **Coliform Bacteria:** Coliform bacteria are a broad group of microorganisms, with fecal coliforms being specific indicators of fecal contamination from human and animal waste. These bacteria are not typically harmful themselves but are used as indicators for the potential presence of harmful pathogens, such as E. coli, enteric viruses, and protozoa[n9].

- **Test Method:** The presence of coliform bacteria in water is usually determined using a membrane filtration method, multiple-tube fermentation method, or presence-absence test. In these methods, water samples are incubated in selective media that encourage the growth of coliform bacteria, and the results are analyzed by counting the number of colonies (CFU/100 mL).
- **Significance:** The presence of coliforms in groundwater suggests that the water may be contaminated with pathogens and is unsafe for drinking or use. The World Health Organization (WHO) recommends that drinking water should have no detectable coliforms (0 CFU/100 mL).

2. **E. coli (Escherichia coli):** *E. coli* is a specific species of fecal coliform that directly indicates contamination from human or animal feces. It is a more reliable indicator of recent fecal contamination and the likelihood

of the presence of other harmful pathogens, such as enteric viruses and parasites.

- **Test Method:** The most common testing method for *E. coli* is enzyme-substrate testing, where water samples are exposed to a substrate that reacts in the presence of *E. coli* enzymes. Alternatively, the membrane filtration and multiple-tube fermentation methods are also used to culture and detect the bacteria.
- **Significance:** The presence of *E. coli* in groundwater indicates a significant risk of waterborne disease. According to the WHO, drinking water should contain zero colonies of E. coli per 100 mL to be considered safe for human consumption.

3. **Total Bacterial Count:** The total bacterial count measures the total number of viable bacteria in a water sample, which includes both pathogenic and non-pathogenic species[n9]. While it does not specifically identify harmful bacteria, a high bacterial count indicates the presence of contamination, often from organic matter or sewage.

- **Test Method:** The plate count method is the most common way to measure total bacterial count. Water samples are diluted and spread over agar plates, which are then incubated. The number of bacterial colonies that grow is counted to estimate the concentration of bacteria in the sample (CFU/mL).
- **Significance:** A high total bacterial count suggests that the water may be contaminated and may require treatment, such as filtration or chlorination, to ensure it is safe for use.

4. **Fecal Streptococci:** Fecal streptococci are bacteria found in the intestines of humans and animals. They are more resistant to environmental conditions than coliform bacteria and can persist in water for longer periods. Their presence is often used to assess fecal contamination, particularly from animal sources.

- **Test Method:** Fecal streptococci are usually tested using the membrane filtration method or multiple-tube fermentation technique, where water samples are incubated in media that select for streptococci species. The colonies formed are counted to estimate the concentration of these bacteria in the water (CFU/100 mL).
- **Significance:** The presence of fecal streptococci suggests that groundwater may be contaminated with animal waste, and the water may not be safe for consumption.

5. **Enterococci:** Enterococci are a subgroup of fecal streptococci that are used as an indicator of fecal contamination. Enterococci are more reliable indicators of water quality than coliforms in many cases, especially in cases where contamination may be from animal sources.

- **Test Method:** Enterococci are usually tested using the most probable number (MPN) method, the membrane filtration method, or the presence-absence method. These methods use specific media that support the growth of enterococci, and the number of colonies is counted.
- **Significance:** Groundwater should be free of enterococci for it to be considered safe for drinking and other uses.

6. **Protozoa (e.g., Giardia and Cryptosporidium):** Protozoa are microscopic parasites that can cause gastrointestinal illness. These organisms are more resilient than bacteria, and their presence in groundwater can be an indication of contamination by sewage, surface water, or animal waste. Protozoa like Giardia and *Cryptosporidium* can survive in groundwater for long periods.[n10]

- **Test Method:** Detection of protozoa is typically done using microscopic examination of water samples, where filtration and staining techniques are used to identify and count the presence of protozoa cysts or oocysts. Immunoassay and PCR (Polymerase Chain Reaction) methods are also increasingly used for more sensitive detection.

- **Significance:** Protozoa can cause serious waterborne diseases, such as giardiasis and cryptosporidiosis. Their presence indicates significant contamination and requires advanced treatment methods such as filtration, UV treatment, or ozone treatment.

7. **Viruses:** Waterborne viruses, such as enteric viruses, can cause a wide range of diseases, including gastroenteritis and hepatitis. Although viruses are rarely tested for directly in groundwater, their presence is a significant concern, especially in regions with poor sanitation.

- **Test Method:** Testing for viruses typically requires advanced techniques, including reverse transcription polymerase chain reaction (RT-PCR), to detect viral RNA. This process involves filtering the water, concentrating any potential viral particles, and then analyzing the genetic material.
- **Significance:** The detection of viruses in groundwater indicates serious contamination and poses significant health risks, especially to vulnerable populations.

8. **Algae:** Although algae are more commonly found in surface water, their presence in groundwater can indicate contamination, particularly in areas where groundwater is connected to surface water. Some types of algae can produce toxins that contaminate the water and pose health risks.

- **Test Method:** Algae are usually detected by microscopic examination of filtered water samples, where algae cells can be counted, and the species identified.
- **Significance:** While algae in groundwater are relatively rare, their presence suggests contamination and could indicate poor water quality, necessitating treatment to remove potential toxins.

The biological testing of groundwater is essential to ensuring water safety and preventing waterborne diseases. Routine monitoring of microbial parameters such as coliform bacteria, *E. coli*, fecal streptococci, enterococci, protozoa, viruses, and algae is necessary for evaluating the extent of contamination and determining whether treatment is needed to make the water safe for consumption and use. Various microbiological testing methods, including membrane filtration, multiple-tube fermentation, enzyme-substrate tests, and PCR, are used to detect these biological contaminants. Water treatment options such as chlorination, filtration, UV treatment, and reverse osmosis are typically employed to address biological contamination in groundwater.

6. Pollution Sources

Urban and Industrial Discharges: In regions like Avaniyapuram and Sakkimangalam, the presence of sewage treatment plants has been linked to groundwater contamination. Studies have shown that sewage pollution in these areas adversely affects water resources, land quality, and poses health risks to both humans and livestock.[P1] Figure 3. Areas such as Thiruppalai and Arittapatti experience groundwater quality issues due to agricultural activities. The use of fertilizers and pesticides leads to elevated levels of nitrates and other contaminants in the groundwater, impacting its suitability for drinking and irrigation.[P2] The Bethaniapuram area faces pollution challenges from industrial activities, particularly from aluminum vessel manufacturing units. Residual waste from these industries is often improperly disposed of along the banks of the Vaigai River, leading to hazardous substances leaching into the groundwater. Extensive sand mining in riverbeds, especially along the Vaigai River, has been reported to lower groundwater levels and degrade water quality. This activity disrupts natural aquifers, leading to reduced groundwater recharge and increased contamination risks. suitability for plants, infrastructure, and industrial equipment .[n5]. Total dissolved solids (TDS) and electrical conductivity (EC) are indicators of salinity and mineral content, which affect water taste, soil quality for agriculture, and potential risks of water salinization. High levels of nitrates and ammonia may suggest contamination from agricultural runoff or sewage, posing health risks, especially to infants taste, health risks, and suitability for irrigation. pH levels help assess the water’s corrosiveness.

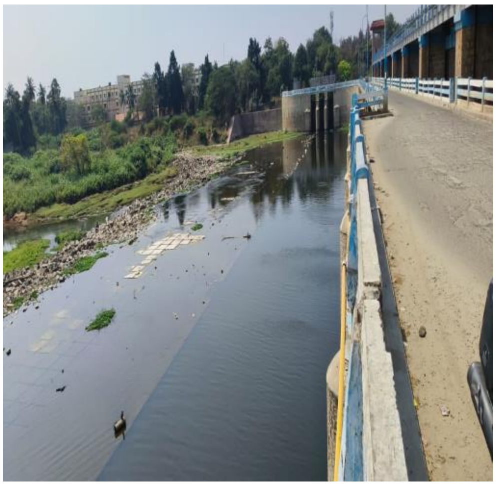

Figure 3 Urban and Industrial Discharges:

6.1. Hydro-Chemical Analysis in Madurai

The pH of groundwater indicates its acidity or alkalinity, influencing the solubility of minerals and contaminants. Groundwater in Madurai district typically shows neutral to slightly alkaline pH values, with some areas experiencing slight acidity due to agricultural runoff. Studies highlight that areas like Arittapatti and Thiruppalai have observed slightly acidic to neutral pH levels, indicative of contamination from fertilizers and organic materials. TDS refers to the concentration of dissolved ions in water, which can affect taste and usability. Groundwater in Madurai district has reported varied TDS levels, with higher concentrations found in areas like Alagarkoil and Vadipatti, which are impacted by industrial effluents and over-extraction. Elevated TDS may indicate pollution from both natural sources, such as mineral leaching, and anthropogenic factors. Hardness is primarily due to the presence of calcium and magnesium ions, which are important for determining the suitability of water for domestic and industrial uses. In Madurai district, groundwater hardness varies, with some areas like Keeramangalam and Melur showing high levels of hardness due to geogenic factors and mineral-rich aquifers. Nitrates and nitrites in groundwater primarily result from agricultural runoff, sewage, and industrial waste[n11]. Elevated levels of nitrate contamination are found in Sakkimangalam and Thiruppalai, which are heavily influenced by agricultural activities. Nitrate contamination poses health risks, particularly in areas relying on groundwater for drinking purposes. Groundwater contamination by heavy metals like lead (Pb), arsenic (As), and cadmium (Cd) is a growing concern in industrial areas. In regions like Bethaniapuram and Pandian Nagar, groundwater is contaminated with heavy metals due to industrial effluents from local factories. These pollutants pose significant health risks, especially when the groundwater is used for domestic purposes. Fluoride contamination is another issue in parts of the Madurai district, with areas like T.Kallupatti and Paramakudi showing concentrations exceeding the permissible limits. High fluoride levels can cause dental and skeletal fluorosis if the water is used for drinking over prolonged periods. Chloride concentrations in groundwater can be an indicator of pollution from sewage, industrial waste, or saltwater intrusion. Elevated chloride levels are found in areas such as Alagarkoil and Madurai city outskirts, primarily due to contamination from sewage effluents and the overuse of chemical fertilizers. The presence of harmful microorganisms such as bacteria, viruses, and protozoa is an indicator of microbial contamination, often originating from sewage or agricultural runoff. Areas like Avaniyapuram and Sakkimangalam show elevated levels of coliforms and other pathogens, making the water unsafe for consumption without proper treatment [45-48].

7. Statistical Evaluation

7.1. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a powerful multivariate statistical technique used for dimensionality reduction and pattern recognition in large datasets. In hydrochemical studies, PCA helps identify the dominant processes influencing groundwater quality by transforming a set of correlated variables into new uncorrelated variables known as Principal Components (PCs). The technique works by standardizing the dataset to eliminate scale differences, computing the covariance matrix, and performing eigenvalue decomposition to extract significant components.[n12] The first principal component (PC1) captures the highest variance in the dataset, while subsequent components (PC2, PC3, etc.) explain progressively less variation. By selecting the most significant components—

typically those with eigenvalues greater than 1 (Kaiser's Criterion) or explaining 85-95% of cumulative variance—PCA reduces data complexity while retaining critical information. Mathematically, PCA involves solving the eigenvalue equation CV=λVCV = \lambda V, where CC is the covariance matrix, VV represents eigenvectors (new coordinate axes), and λ\lambda are eigenvalues (variance explained). Once principal components are extracted, the original data is projected onto these new axes using P=ZVP = ZV, where PP is the transformed dataset and ZZ is the standardized data matrix. In hydrochemical analysis, PCA helps classify groundwater samples based on chemical composition, detect contamination sources (e.g., industrial effluents, saline intrusion, or agricultural runoff), and interpret geochemical processes such as weathering, ion exchange, and anthropogenic influence. For instance, if PCA shows that TDS, Na+, Cl−, and SO_4^{2-} load heavily on PC1, it may indicate seawater intrusion or industrial contamination, whereas Ca^{2+}, Mg^{2+}, and HCO_3^- dominating PC2 might suggest carbonate dissolution. The results can be visualized through biplots and scree plots, aiding in hydrochemical interpretation. PCA can be implemented using software tools like SPSS, Python (scikit-learn), R (FactoMineR, psych), MATLAB, and OriginPro, which provide efficient computational methods for eigenvalue decomposition, data transformation, and visualization. By simplifying complex groundwater quality datasets, PCA allows for better decision-making in sustainable water resource management, pollution control, and groundwater conservation strategies.

7.2. Hierarchical Cluster Analysis (HCA)

Hierarchical Cluster Analysis (HCA) is a multivariate statistical technique used to classify groundwater samples based on their hydrochemical properties, allowing for the identification of water quality patterns and pollution sources. [n13]HCA works by calculating the similarity or dissimilarity between samples using distance metrics such as Euclidean Distance, which measures the straight-line difference between two data points, or Mahalanobis Distance, which accounts for correlations between variables. Once the distance matrix is established, clusters are formed using linkage methods such as single linkage (minimum distance), complete linkage (maximum distance), average linkage (mean distance), or Ward's method (variance minimization). These methods define how individual samples or groups of samples are merged iteratively until all data points belong to a single cluster. The results of HCA are typically visualized using a dendrogram, a tree-like diagram that represents hierarchical relationships between groundwater samples, where shorter branch lengths indicate higher similarity. In hydrochemical studies, HCA is useful for distinguishing natural hydrochemical processes (e.g., rock-water interactions, carbonate dissolution) from anthropogenic influences (e.g., agricultural runoff, industrial discharge, saline intrusion). For instance, if groundwater samples form distinct clusters based on Total Dissolved Solids (TDS), sodium (Na^+), and chloride (Cl^-) concentrations, it may indicate contamination from seawater intrusion or industrial effluents, whereas clustering based on calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) may suggest natural mineral dissolution. HCA can be implemented using statistical software such as SPSS, R (hclust function), Python (SciPy and Scikit-learn), MATLAB, and OriginPro, which allow for efficient computation of distance matrices, cluster formation, and dendrogram visualization. By grouping groundwater samples with similar characteristics, HCA helps in identifying pollution hotspots, assessing spatial variability in water quality, and guiding sustainable groundwater management strategies.

7.3. Spatial Analysis Using Geographic Information Systems (GIS)

Spatial Analysis using Geographic Information Systems (GIS) is a crucial technique in hydrochemical studies for mapping and analyzing groundwater quality variations across a region. GIS integrates geospatial data with hydrochemical parameters to visualize contamination hotspots, assess spatial trends, and support sustainable water management. One of the key techniques in GIS-based hydrochemical analysis is interpolation, which predicts groundwater quality at unmeasured locations based on sampled data points. Methods like Inverse Distance Weighting (IDW), Kriging, and Spline interpolation are commonly used to generate spatial distribution maps for parameters such as pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and major ions (Na^+, Cl^-, SO_4^{2-}, HCO_3^-). Kriging, a geostatistical method, is particularly effective as it considers spatial autocorrelation and provides better accuracy in predicting groundwater quality patterns.[n14] Additionally, GIS-based overlay analysis helps in correlating hydrochemical properties with land use, soil type, industrial zones, and agricultural activities, aiding in identifying potential contamination sources. Spatial clustering techniques, such as *hotspot analysis (Getis-Ord Gi)**, can further highlight areas of significant water quality degradation. GIS software like ArcGIS, QGIS, and Google Earth Engine provides powerful tools for hydrochemical mapping, groundwater vulnerability assessment, and decision-making in water resource management. By leveraging GIS in hydrochemical studies, researchers and policymakers can identify pollution sources, monitor long-term groundwater changes, and develop effective remediation strategies, ensuring sustainable water management in regions like Madurai District.

7.4. Water Quality Index (WQI)

The Water Quality Index (WQI) is a numerical tool used to assess and categorize groundwater quality by aggregating multiple hydrochemical parameters into a single value. [n15] WQI simplifies complex water quality data, making it easier to interpret and communicate the overall suitability of groundwater for drinking, irrigation, and industrial use. The calculation of WQI involves selecting key water quality parameters such as pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), Dissolved Oxygen (DO), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), and anions (Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-). Each parameter is assigned a weight (Wi) based on its relative importance to water quality and human health, following guidelines from organizations like the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). The Relative Weight (Wi') is determined as $Wi' = Wi / \sum Wi$, ensuring that more critical parameters have a greater impact on the final index. The Quality Rating Scale (Qi) is calculated for each parameter by comparing its observed concentration with the permissible standard values. The WQI is then computed using the formula $WQI = \sum(Wi' \times Qi) / \sum Wi'$, where a lower WQI indicates better water quality. Based on the WQI score, water is categorized as Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100), or Unsuitable for Drinking (>100). In hydrochemical studies, WQI helps in identifying groundwater pollution hotspots, assessing seasonal variations in water quality, and guiding water resource management strategies. GIS-based spatial mapping of WQI further enhances visualization by highlighting areas requiring urgent remediation. Tools like SPSS, Python (Pandas, NumPy), R (waterQuality package), and ArcGIS are commonly used for WQI computation and mapping. By integrating WQI into groundwater studies, researchers and policymakers can make informed decisions to ensure safe and sustainable water supply.

7.5. Sustainable Management of Groundwater in Madurai

Groundwater is a vital resource for drinking, agriculture, and industrial activities in Madurai, but increasing urbanization, over-extraction, and contamination pose significant challenges to its sustainability. Implementing sustainable groundwater management is essential to ensure long-term water availability and quality for future generations.

- **Understanding Groundwater Challenges in Madurai. Over-extraction:** High groundwater demand for agriculture and domestic use leads to depletion.
- **Seasonal Variability:** Uneven rainfall distribution affects groundwater recharge.
- **Water Contamination:** Agricultural runoff, industrial discharge, and poor waste disposal pollute aquifers.
- **Saline Intrusion:** Over-pumping in some areas near water bodies leads to saline water intrusion into freshwater aquifers.
- **Groundwater Recharge and Conservation Strategies. Rainwater Harvesting:** Implementing rooftop rainwater harvesting and percolation pits in urban and rural areas to

enhance groundwater recharge.

- **Check Dams and Percolation Ponds:** Constructing check dams, farm ponds, and artificial recharge structures in dry regions of Madurai to increase water percolation.
- Forest and Vegetation Cover: Promoting afforestation and watershed management to reduce surface runoff and improve infiltration.
- **Pollution Control and Water Quality.** Protection**.** Wastewater Treatment: Strengthening sewage treatment plants (STPs) and promoting decentralized wastewater treatment to reduce contamination of groundwater sources.
- **Agricultural Best Practices:** Encouraging organic farming, controlled fertilizer use, and drip irrigation to minimize nitrate and pesticide contamination.
- **Industrial Regulations:** Implementing strict monitoring of industrial effluents and ensuring industries follow zero-liquid discharge (ZLD) policies.

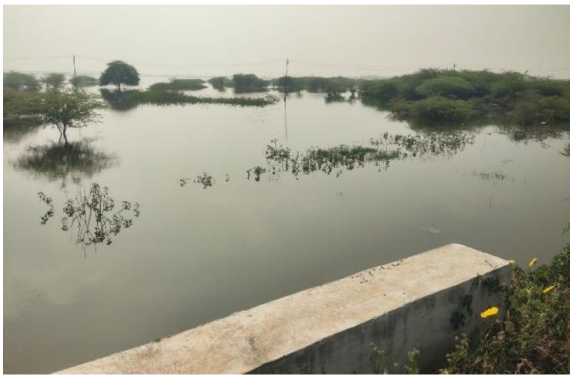

Figure 4 Smart Groundwater Monitoring

- **Smart Groundwater Monitoring and Data Management. GIS-Based Hydrochemical Mapping:** Using Geographic Information Systems (GIS) to create real-time maps of groundwater quality and quantity in different zones of Madurai.
- **IoT and Sensors:** Installing smart water meters and sensors in borewells and reservoirs to monitor water levels and prevent over-extraction[n16].
- **Hydrochemical Analysis:** Conducting periodic water quality testing and statistical evaluations (PCA, HCA, WQI) to assess pollution trends.

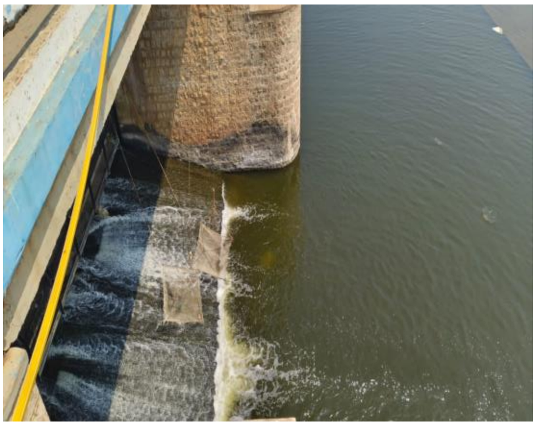

Figure 5 Groundwater Monitoring

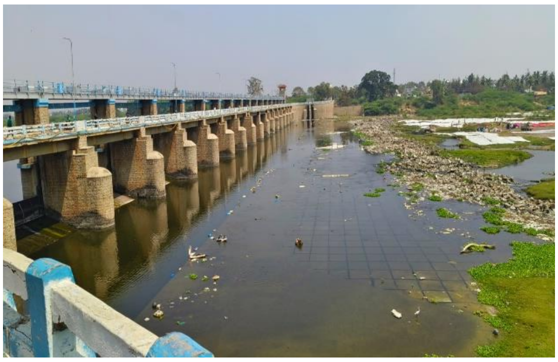

Figure 6 Groundwater Monitoring

- **Community Participation and Policy Implementation. Public Awareness Programs:** Educating local communities on water conservation techniques, rainwater harvesting, and responsible groundwater usage.
- **Government Policies and Regulations:** Implementing strict groundwater extraction policies and incentives for sustainable agricultural and industrial water use.
- **Water User Associations (WUAs):** Encouraging local farmers and residents to participate in community-led water management initiatives.
- **Future Directions for Sustainable Water Management. Desalination and Water**

Reuse: Exploring desalination of saline water and advanced water recycling methods for non-potable uses.

- **Climate-Resilient Water Management:** Integrating climate data with groundwater policies to prepare for droughts and monsoon variations.
- **Integrated Water Resource Management (IWRM):** Combining surface and groundwater management for balanced water allocation among sectors, shown in Figure 4 to Figure 6.

Conclusion

Sustainable groundwater management is crucial for ensuring long-term water security in Madurai, where increasing urbanization, over-extraction, and contamination threaten groundwater availability. Implementing groundwater recharge and conservation strategies such as rainwater harvesting, check dams, percolation ponds, and afforestation helps restore groundwater levels. Additionally, pollution control measures, including wastewater treatment, regulated agricultural practices, and strict industrial policies, are essential for maintaining water quality. Advanced tools like GIS-based hydrochemical mapping, IoT-enabled monitoring, and statistical analyses (PCA, HCA, WQI) provide valuable insights into groundwater conditions. Community participation, government policies, and integrated water resource management (IWRM) further strengthen conservation efforts. By adopting a holistic approach that combines scientific research, technology, policy enforcement, and public awareness, groundwater sustainability in Madurai can be effectively achieved, ensuring a safe and reliable water supply for future generations.

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