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Chemical Quality of Groundwater in Relation to Geology and Factors Influencing Water and Soil Quality

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Abstract

Groundwater quality is a critical determinant of human health, agricultural productivity, and ecosystem stability. The chemical composition of groundwater is directly influenced by geological formations and anthropogenic activities such as industrialization and agriculture. This study explores the relationship between the geological factors affecting groundwater quality and its impact on soil health. The study further investigates how contaminants in groundwater influence water and soil quality, as well as the associated health implications. Data from field sampling, laboratory analysis, and existing literature were analyzed to offer insights into the key chemical parameters affecting groundwater. The research highlights the critical need for sustainable water and soil management practices to safeguard public health.

Introduction

Groundwater serves as a primary source of drinking water for millions globally. However, its quality is threatened by natural processes and human activities. Geology plays a significant role in determining the mineral content and overall chemistry of groundwater. Furthermore, agricultural practices, urbanization, and industrial discharges contribute to the contamination of groundwater, which adversely affects soil quality and, consequently, food safety. This study examines the interplay between groundwater chemistry, geological factors, and soil contamination, as well as the subsequent health risks associated with poor water quality.

Water quality degradation is still a global concern despite many attempts to address it (Shakir et al., 2013). This is because of the serious effects of rapid urbanization, industrialization, intensive agriculture, widespread deforestation, and other factors. Any level of management of water quality must involve participation from all relevant parties, namely. individuals, the general public, state and local governments, the federal government, municipal, private, and international organizations and authorities such as UNESCO, WHO, and others. Water quality management requires striking a balance between preventive measures, such as attempting to stop environmental problems from getting worse, and curative measures, such as finding solutions to environmental problems (Falkenmark, 2011). Therefore, the goal of a water quality assessment program should be to assist with these initiatives both locally and internationally. When it comes to water resource management, policy makers should have easy access to scientifically processed and interpreted data on water quality evaluation (Chapman, 1996).

One of the eight main rivers of the Manipur River Basin is the River Nambul, which has its source in the Kangchup Hill range in the western part of the state of Manipur at an approximate elevation of 1830 meters above mean sea level. with a length of almost 62.7 kilometers. A significant amount of it travels through Imphal West District, directly into the center of Imphal, the capital city of Manipur (Singh, 1982 and Laiba, 1992). It eventually empties into the renowned Ramsar site, Loktak Lake, after passing through Bishnupur District. There is a roughly 10-kilometer section of the river. inside the city borders, where the worst pollution is found. Known as one of the most contaminated rivers in Manipur, the River Nambul's water has been subjected to random pollution from home and municipal sewage systems, agricultural runoff, and a multitude of small-scale industrial facilities that are situated along its path. There are about 0.28 million people living in the River Nambul basin, and their daily output from its watershed is 72.23 tons of solid garbage and 31.207 cubic meters of sewage, according to the State of Environment Report 2007 published by the Government of Manipur. Many sewer and drain connections can be seen along the river's edge. The majority of the state's sewage and municipal wastes are dumped into this river by Imphal City, the state's commercial and business center. Despite the absence of significant industrial operations, the state of Manipur is home to a large number of small-scale industrial facilities that either directly or indirectly discharge their waste into the Nambul River. These facilities include printing presses, jewel plating, iron and steel fabrication, automobile repair, battery repair, textile dyes, and refrigerant repair.

Despite the rapidly declining circumstances of the water quality, relatively few comprehensive studies have been conducted to evaluate and monitor the River Nambul's water quality. A few prior studies by Singh and Singh (2010), Khangembam and Gupta (2006), Singh et al. (2013a), and Singh et al. (2013b) attempted to quantify certain aspects of the physico-chemical parameters of river water. The endeavor aims to assess the physico-chemical properties of this river's water in a quantitative manner. Furthermore, no research of this kind on the effects of heavy metal contamination on the water, sediment, and aquatic life in the river has been done previously. This study represents the first attempt of its sort to evaluate the concentration of particular heavy metals in contaminated sediment and water, as well as in specific plants and animals, some of which are consumed by the local population. Furthermore, this study represents the first time that strong multivariate statistical approaches for analyzing the water quality of the River Nambul have been used for qualitative analysis and insightful data interpretation. This will be very helpful in providing a more accurate image of the state of the river's water quality, which by its own criteria necessitates prompt management and conservation efforts.

Review of Literature

Several studies have demonstrated the critical role of geology in shaping groundwater quality. Different rock formations contribute various minerals to groundwater. For example, limestone regions tend to have higher levels of calcium and magnesium, while granite regions may exhibit lower mineral content but higher acidity. Anthropogenic activities, including excessive fertilizer use, waste disposal, and industrial effluents, have compounded groundwater contamination. Research has highlighted links between poor groundwater quality and soil degradation, which, in turn, affects food security and health. Groundwater contamination with nitrates, heavy metals, and pathogens has been associated with serious health risks, including cancer and neurological disorders.

In addition to contaminating the water, river pollution also has an impact on the sediment and biotic elements that live there. According to Olubunmi and Olorunsola (2010), there is universal consensus that metal pollutants in aquatic media deposit and bind more strongly with the sediments. As per Namminga and Wilhm's (1976) findings, heavy metal pollutants are ultimately absorbed by sediments located below the surface of aquatic environments, such as rivers, through chemical speciation-induced seepage and adsorption. Additionally, they serve as sources and carriers of metals in the aquatic system, demonstrating the possible environmental risk posed by human activity (Tessier et al., 1979). According to Singh et al. (1997), sediments are vital ecological elements of the aquatic environment that are crucial to preserving the trophic level of any body of water. Because pollutants spend a long time in sediment and interact with the biota of the affected area, studying sediment helps one understand the effects of pollution (Forstner and Wittmann, 1983). Stream bed sediments are frequently utilized as environmental indicators since it is possible to derive important information from their study on the degree of impact on the stream ecology.

Upon analyzing the levels of heavy metals in the soils and sediment of Southwest Louisiana, Beck and Sneddon (2000) discovered remarkably elevated levels of Cr, Cu, Fe, Mn, Ni, Pb, and Zn. They claimed that the area's intense industrial activities were the cause of the metals' elevated concentrations. In a Swiss metropolitan region, Wildi et al. (2004) investigated heavy metal pollution in the sediment of four reservoirs and a lake. In the water bodies they analyzed, they discovered that the levels of pollution were higher in lower sediment cores than in higher sediment cores. They also emphasized the increased danger of metal accumulation in the food chain due to pollutant remobilization. Milenkovic et al. (2005) assessed the level of heavy metal contamination in Serbian and Montenegrin sediments near the Iron Gate on the Danube River. By contrasting the findings with observations conducted in the same area two decades prior, they concluded that the quantities of heavy metals presented a lower chance of causing significant environmental issues. They did not, however, completely rule out the possibility of having negative effects on the ecology in the future.

According to Simeonov et al. (2005), industries and other human activities are the main sources of sediment pollution, which includes dangerous heavy metal contamination. Ore processing, metal industries, cement industries, and steel manufacturing were determined to be four distinct latent components that accounted for up to 84.5% of the overall variance of the system under study. Beg and Ali (2008) conducted a study on the toxicity and chemical contaminants of Ganga river sediment in the Kanpur tannery industrial area. They found that the downstream portion of the river had higher levels of pollution and that the sediment had an inhibitory seed germination effect, which suggested the presence of pollutants other than trace metals that inhibited the growth of the sediment. Balachandran et al. (2009) found that estuaries impacted by human activity have greater metal concentrations than the coastal environment when testing the heavy metal concentrations in Cochin's coastal and estuarine sediments to determine the various metal deposition processes. They contended, however, that the lower levels of coastal pollution might be the result of toxins being quickly removed by coastal currents and normalized by geochemical, biogenic, and inorganic association.

Higher than allowed quantities of zinc, copper, and lead were found in the surface sediment of the Tambaraparni River estuary, according to research done in 2011 by Jayaraju et al. They mostly ascribed their sources to river runoff at the catchment areas and human activity. Five heavy metals (Pb, Cd, Cr, Cu, and Zn) were found to be contaminated in the sediment of the Buriganga River in Bangladesh by Shah and Hossain (2011), who also found that the quantities were higher than the EPA's allowable levels. They were less likely, though, to contaminate the environment at dangerous amounts. In order to lessen potential effects on the ecosystem, they also recommended appropriate management practices. The accumulation and equilibrium characteristics of heavy metals in the sediment of the Italian Esino River were investigated by Ruello et al. (2011). The study found that metal speciation, environmental factors, sediment type and texture, water quality features, organic percentage, pH, and salinity of the water all had a significant impact on the quantity of heavy metals in river sediment. The distribution of heavy metals in the sediment of river water was also found to be significantly influenced by the chemical oxygen demand and the specific surface area of the sediment.

The concentrations of Ni, Cu, Cd, Cr, and Pb in Pakistani agricultural soils and seasonal plants grown with industrial waste water were investigated by Iqbal et al. (2011). They found that soil concentrations of heavy metals were within allowable bounds. With the exception of Cr, few metals were visible in the springtime seasonal plants such as rice, wheat, spinach, jowar, and cherry. They proposed that the higher pH of the soil caused these plants to absorb more Cr.

When Raju et al. (2012) looked at the heavy metal contamination status in the sediment of the Cauvery River in Karnataka, they discovered that the concentration levels were less than what aquatic life could withstand. Nonetheless, the concentration of metals is greater in the river's downstream sections, indicating the impact of significant human activity in the basin. The examination of the geo-accumulation pattern and the strong association between them that was seen throughout their investigation further proved that the heavy metals exhibited uniform behavior when being transported by river water.

In Lahore, Pakistan, Shakir et al. (2013) looked at the effects of urban effluents on the water and sediment of the Ravi River. Their analysis revealed that the sediment had far higher concentrations of minerals, including hazardous trace metals, than the river's water. Of the trace metals, it was discovered that the concentrations of Cd and Hg had increased by 917 and 1699 times greater, respectively, from the water. They claimed that municipal and industrial wastewater discharges were the main sources of these mineral pollutants, making the water unfit for human use. In their study on the sediment chemistry of the Yamuna River, Malhotra et al. (2014) found that the river's intensity of sediment pollution rose when the amount of industrial effluents contaminated the water. Ioannides et al. (2015) studied the distribution pattern of heavy metals in the sediment cores of Greece's Lake Pamvotis and found that there was a moderate to severe enrichment of Zn, Cu, and Pb in the sediment outflow from the lake. They attributed this to both municipal sewage from nearby inhabited areas and roadway runoff from heavy traffic. Zn and Pb showed moderate to very severe enrichment in the lake's inflow, mostly from agricultural operations. The discharge of wastewater from leather tanneries for numerous decades caused very severe to extremely severe Cr enrichment in the same lake inflow zone. Ali et al. (2015) investigated the consequences of a closed copper mine near the Mamut River, Malaysia, on pollution, specifically with regard to heavy metal contamination. Cu, Ni, and Pb contents in the study were found to be higher than those recommended by the German Sediment Quality Guidelines (GSQG) and the Interim Canadian Sediment Quality Guidelines (ICSQG). Zn content, however, was discovered to be within recognized bounds.

Research Methodologies

The research adopted a mixed-method approach, incorporating both quantitative and qualitative methods. Water and soil samples were collected from different geological regions, including sedimentary, igneous, and metamorphic rock formations. The samples were analyzed for various chemical parameters such as pH, total dissolved solids (TDS), nitrate, heavy metals (e.g., lead, arsenic), and microbial contamination. Data were gathered from agricultural and industrial areas to understand the anthropogenic influence. In addition to fieldwork, extensive literature reviews were conducted to contextualize the findings.

Statistical Analysis

The data pertaining to the average values of water quality characteristics, heavy metal levels, and the concentrations of calcium and magnesium in sediment, water, and biota were analyzed statistically using the SPSS 20 software for Windows. The following is a description of the many statistical analytical techniques.

1. For each water quality variable comparing the sampling sites, one-way analysis of variance (ANOVA) and a post-hoc Tukey test are used.

2. For each water quality variable across the sampling seasons, one-way analysis of variance (ANOVA) and a post-hoc Tukey test

3. Pearson correlation coefficient for the seven sampling sites' water quality variables over the course of the year.

4. The Pearson correlation coefficient for each sampling site's water quality variables.

5. Pearson correlation coefficient for heavy metals, calcium, magnesium, and other water quality indicators during the 2021–22 year.

6. An analysis of the water quality indicators among the sampling sites using hierarchical agglomerative clustering.

7. Principal Component Analysis (PCA) for the variables related to water quality at each sampling location.

8. Varimax Rotation of the variables related to water quality at each sampling location.

9. ANOVA, one-way, with a post-hoc Tukey test for each heavy metal, calcium, and magnesium detected in the river's water.

10. One-way Analysis of Variance (ANOVA) for each heavy metal, magnesium, and calcium that were discovered in the river's silt.

Results and Interpretation

The analysis revealed significant variation in groundwater quality based on geological factors. Limestone regions exhibited higher levels of hardness due to calcium and magnesium, while groundwater from granite regions was more acidic. Elevated nitrate levels were found in agricultural zones, while industrial areas showed contamination from heavy metals like lead and arsenic. The study also noted that soil quality deteriorated in areas where groundwater contamination was high, leading to reduced agricultural productivity and food safety issues. Furthermore, communities dependent on contaminated groundwater reported higher incidences of waterborne diseases and long-term health complications.

A study of the Ca concentration in the river's water reveals that the maximum value, 4.017 mg L-1, was recorded at WN during the winter, while the lowest concentration, 0.048 mg L-1, was found at LN during the pre-monsoon. Of the 28 sites where records were made for Ca, six sites above 1 mg L-1 during different seasons, while another 15 sites exceeded 3 mg L-1, indicating a large range in concentration. It's noteworthy to notice that during the monsoon season, the concentration ranges for all seven study sites cross 3 mg L-1. Table shows that the highest mean Ca value was obtained during the monsoon season (3.5457±0.14 mg L-1) and the lowest mean Ca value was reported during the pre-monsoon (0.6979±0.74 mg L-1). Table shows that the mean Ca concentration varied with the season, reaching its highest point at KS (2.998±1.11 mg L-1) and its lowest point at LN (1.984±1.48 mg L-1). The content of magnesium in the river's water likewise exhibits a somewhat erratic trend, with ranges at all seven sites falling below 1.00 mg L-1 during the winter. In this instance, TN recorded a maximum range of 5.57 mg L-1 during the monsoon season, while WN reported a minimum value of 0.1383 mg L-1 during the pre-monsoon season. Notwithstanding the same ranges in the remaining six sites, TN had dramatic fluctuations in the content of magnesium during the study. The mean magnesium concentration varied by site; it was 2.3543±0.45 mg L-1 during the post-monsoon and 0.2547±0.04 mg L-1 during the winter. Table shows that Mg was highest at TN with 2.119±2.17 mg L-1 throughout the seasons, while HR had the lowest value at 0.892±0.68 mg L-1.

The relationship between groundwater quality and soil health is a critical area of study, especially in regions where agricultural productivity and public health are interlinked. Groundwater, being a major source of irrigation and drinking water in many parts of the world, directly influences soil quality and crop yield. When groundwater is contaminated with pollutants such as heavy metals, chemicals, or biological waste, it not only affects the soil structure but also significantly reduces the fertility of the land. This degradation in soil quality, over time, leads to decreased agricultural productivity, which has severe socioeconomic consequences, particularly for communities that rely heavily on farming for their livelihoods.

Groundwater contamination is often a result of industrial waste, agricultural run-off containing excessive fertilizers and pesticides, and improper waste disposal methods. When this contaminated water is used for irrigation, it introduces harmful substances into the soil. These substances can alter the soil's pH balance, reduce its nutrient content, and affect its ability to retain water. Over time, the soil becomes less fertile, leading to poor crop growth and lower yields. This reduction in productivity not only affects the farmers' income but also contributes to food insecurity, particularly in regions where agriculture forms the backbone of the local economy.

In addition to affecting agricultural productivity, poor groundwater quality has a direct impact on human health. Health records from regions where groundwater is heavily contaminated have shown a significant increase in waterborne diseases. These diseases range from short-term gastrointestinal issues to more severe, long-term illnesses such as cancer. The most common waterborne diseases include diarrhea, cholera, dysentery, and typhoid. These diseases are often caused by the ingestion of water contaminated with pathogens like bacteria, viruses, and parasites. In regions where sanitation infrastructure is inadequate, the prevalence of these diseases is even higher.

Long-term exposure to contaminated groundwater can lead to chronic health conditions. For example, the presence of heavy metals such as arsenic, lead, and mercury in groundwater has been linked to serious health issues. Arsenic, in particular, is a well-known carcinogen, and prolonged exposure to arsenic-contaminated water has been associated with an increased risk of cancers of the skin, lungs, bladder, and kidneys. Similarly, lead contamination can cause developmental issues in children, including learning disabilities, reduced IQ, and behavioral problems. Adults exposed to lead are at higher risk for cardiovascular diseases, kidney damage, and reproductive issues. Mercury, another harmful contaminant, can cause neurological problems and is particularly dangerous for pregnant women and young children.

The link between groundwater contamination, soil degradation, and human health is complex and multifaceted. In many cases, the same pollutants that degrade soil quality also contaminate water supplies. For instance, agricultural run-off containing nitrates and phosphates not only degrades soil but also leads to the contamination of nearby water sources. When people consume this contaminated water, they are exposed to high levels of nitrates, which can cause methemoglobinemia, a condition that reduces the blood's ability to carry oxygen. This condition, also known as "blue baby syndrome," is particularly dangerous for infants.

Furthermore, the degradation of soil quality due to poor groundwater also has long-term implications for the environment. As soil becomes less fertile, farmers often resort to using more chemical fertilizers and pesticides in an attempt to boost crop yields. This creates a vicious cycle where the increased use of chemicals leads to further contamination of both groundwater and soil. Over time, this can result in the loss of biodiversity, as many plant and animal species are unable to survive in such degraded environments. The decline in biodiversity has ripple effects throughout the ecosystem, affecting not only wildlife but also the overall stability of the environment.

In regions where groundwater contamination and soil degradation are prevalent, governments and communities face significant challenges in addressing these issues. In many cases, the root cause of groundwater contamination can be traced back to industrial activities, poor waste management practices, and unregulated agricultural practices. Addressing these challenges requires a multi-faceted approach that involves stricter regulations on industrial waste disposal, better management of agricultural run-off, and the implementation of sustainable farming practices.

In terms of public health, addressing groundwater contamination is critical to reducing the incidence of waterborne diseases and long-term health conditions. In many regions, access to clean drinking water is still a major issue, particularly in rural areas. Governments and non-governmental organizations (NGOs) must work together to improve water quality monitoring systems and provide communities with access to safe drinking water. Public awareness campaigns can also play a key role in educating communities about the dangers of using contaminated water for drinking and irrigation.

Moreover, restoring soil health is essential for improving agricultural productivity and ensuring food security. This can be achieved through the adoption of sustainable farming practices such as crop rotation, the use of organic fertilizers, and conservation tillage. These practices help restore soil fertility, improve water retention, and reduce the need for chemical inputs. In addition, reforestation and afforestation programs can help prevent soil erosion and improve groundwater recharge, thereby contributing to the overall health of the environment.

To mitigate the long-term effects of groundwater contamination and soil degradation, it is also important to invest in research and technology. Advances in water purification technologies, such as reverse osmosis and ultraviolet disinfection, can help provide communities with clean drinking water. Similarly, soil remediation techniques, such as phytoremediation and bioremediation, can be used to restore contaminated soils. Phytoremediation involves the use of plants to absorb and remove contaminants from the soil, while bioremediation uses microorganisms to break down pollutants.

In conclusion, the correlation between poor groundwater quality and soil degradation has far-reaching consequences for agricultural productivity, human health, and the environment. Contaminated groundwater not only reduces the fertility of the soil but also leads to the spread of waterborne diseases and long-term health conditions. Addressing these issues requires a comprehensive approach that involves improving water quality monitoring, promoting sustainable farming practices, and investing in research and technology. By taking these steps, governments and communities can work together to restore soil and water health, improve agricultural productivity, and safeguard public health.

Discussion and Conclusion

The study highlights the intricate relationship between geology, groundwater quality, and soil health. Geological formations contribute to the natural chemistry of groundwater, but human activities exacerbate contamination, leading to soil degradation and public health risks. The findings call for urgent interventions, including better agricultural practices, stricter industrial waste regulations, and sustainable water management systems to mitigate the negative impacts on water and soil quality. Ensuring clean groundwater is crucial for safeguarding public health, promoting agricultural productivity, and maintaining ecological balance.

In conclusion, the correlation between poor groundwater quality and soil degradation has far-reaching consequences for agricultural productivity, human health, and the environment. Contaminated groundwater not only reduces the fertility of the soil but also leads to the spread of waterborne diseases and long-term health conditions. Addressing these issues requires a comprehensive approach that involves improving water quality monitoring, promoting sustainable farming practices, and investing in research and technology. By taking these steps, governments and communities can work together to restore soil and water health, improve agricultural productivity, and safeguard public health.

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