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Geology and Chemical Quality of Groundwater: Health Implications from Soil and Water Contamination

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Abstract

This paper examines the impact of geological factors and human-induced changes on the chemical quality of groundwater. By analyzing the chemical parameters of groundwater, the research assesses the influence of soil quality and human health in different geographical regions. The study addresses the health risks associated with contaminated groundwater, including the presence of nitrates, heavy metals, and pathogens. Through extensive field sampling, laboratory tests, and data analysis, this paper seeks to offer solutions for improving groundwater and soil quality while mitigating health risks.

Introduction

Groundwater is vital for human consumption, agriculture, and industrial activities, yet its quality is increasingly under threat due to geological and anthropogenic factors. The geology of an area determines the baseline mineral content of groundwater, while human activities such as agriculture, industrialization, and waste management add contaminants that exacerbate water and soil degradation. This paper seeks to understand how geological and human factors affect groundwater chemistry, soil quality, and the subsequent health impacts on communities.

Water scarcity for daily use is exacerbated by pollution in freshwater. Lakes, rivers, and streams that are considered freshwater are susceptible to pollution by humans. Construction, industrialization, and agriculture near rivers and streams can contaminate the environment and alter its balance. Water entering streams from industrial or agricultural sectors can contaminate them.

Every year, the amount of water consumed rises due to the economy's and population's rapid development. Numerous contaminants are released into bodies of water. This clearly exacerbates the already detrimental effects of insufficient water resources and inefficient water use on the aquatic environment. Rivers are among the most susceptible bodies of water to contamination because they remove runoff from agricultural areas and wastewater from cities and industries into their enormous drainage basins. Surface waters are degraded and made less suitable for use for drinking, industry, agriculture, recreation, and other uses due to a combination of natural and anthropogenic factors (e.g., erosion, weathering of crustal materials, changes in precipitation inputs, and increased consumption of water resources) (Carpenter et al., 1998; Jarvie et al., 1998).

Numerous researchers in India have examined the level of pollution in our ecosystems. According to Prasantha and Nayar (2000), one of the issues facing both developed and developing nations is the pollution of water, air, and marine ecosystems, which is caused by industrial and other waste. One issue that both developed and developing nations must deal with is the pollution of the water, air, and marine environment caused by industrial and other wastes (Prasantha and Nayar, 2000). As rivers pass through large cities, home and industrial wastes have a significant impact on the water quality of the rivers (Padmanabha and Belagali, 2007). This alters the water's chemical and physical properties, changing its quality for various purposes (Geetha and Divvakar, 2008). River water can purify itself to some extent, but most of the time the amount and quality of wastes and effluent that are released into the environment exceeds this ability (Aggarwal et al., 2000).

Numerous studies on the limnological elements of river surface water quality have been conducted all over the world. The studies by Baig et al. (2010) on the Chitral River in Pakistan's North West Frontier Province (NWFP), Alam et al. (2007) on the Surma River, Adeyemo et al. (2008) on the physico-chemical parameters and nutrient load of river sediments in Nigeria, Bhutiani and Khanna (2007) on the Suswa River, and Pejman et al. (2009) on the spatial and seasonal variations of water quality of the Haraz River Basin, Iran, may all be mentioned. These studies revealed the importance of taking seasonal variation in parameter assessment into account when assessing water quality. The main factors influencing differences in water quality throughout the year in the Haraz river basin are temperature, nitrate, total solids, and discharge.

Review of Literature

Groundwater quality is shaped by multiple factors, including the geological makeup of an area. Studies have shown that carbonate rocks contribute to high hardness in water due to calcium and magnesium, while areas with volcanic rock are more prone to heavy metal contamination. Human activities also play a significant role in groundwater pollution. Fertilizer runoff from agriculture introduces nitrates into groundwater, while industrial activities contribute heavy metals such as arsenic and lead. Both contaminants pose severe health risks, including methemoglobinemia and various forms of cancer. The literature also links degraded soil quality to poor crop yield and nutrient deficiencies, affecting food security.

Many researchers have concentrated metal analysis around a range of creatures, especially fish, plants, and microorganisms, because of how simple it is to monitor metal concentrations through the study of organisms living in the medium. In a previous investigation, Oertel (1991) looked studied Cladophora glomerata (L) Kutz, which is found in the Danube River in Hungary, and its capacity to accumulate heavy metals. According to reports, the plant that worked well as a bio-indicator had a notable accumulation difference between its upper and lower layers, where twice as much accumulation capability was discovered. In a different investigation, adult barnacles (Elminius modestus Darwin) from the Waitemata and Manukau Harbours in the Auckland region of New Zealand were found to have different concentration levels of Cd, Pb, Cu, and Zn (1992–1992). According to Guzman and Jarvis (1996), industrial contamination can be easily detected by looking for corals in the maritime environment. Through short-term evaluation, they carried out long-term analyses of metals like phosphorous, lead, and cadmium as well as several other metals. Corals have the potential to be used as pollutant tracers, since they have confirmed through this process. Locatelli (2000) presented two approaches in an effort to establish trustworthy analytical methodologies for accurate sample mineralization for the study of heavy metal concentration in aquatic species, yielding exact and accurate results. These are: a) using differential pulse anodic stripping voltammetry (DPASV) to simultaneously determine Cu, Pb, Cd, and Zn; and b) using cold vapour atomic absorption spectroscopy (CV-AAS) to determine Hg while incorporating novel sample dissolution techniques, particularly for mussels, clams, and fish.

Numerous employees have been monitoring metal contamination in soil and water by utilizing a range of organisms. Vinodhini and Narayanan (2008) conducted laboratory experiments on freshwater fish, specifically Cyprinus carpio, or common carp, and found that fish exposed to contaminated water systems experienced bioaccumulation of metals in their organs. They discovered that the concentration of heavy metals increased in the liver over time. Independent reports on heavy metal contamination in freshwater snails in rice fields and freshwater mussels in the Thames River were also made by Ismail (1994) and Manly and George (1977).

Jentschke and Godbold (2000) attempted to illustrate the potential methods via which ectomycorrhizas mitigate the toxic metal stress that impacts the host plant, which underlies the significance of ectomycorrhizas to plant productivity. It is clear that fungi that are tolerant of metals can help reduce the toxicity of metals to forest seedlings. Additionally, Baath et al. (1998) observed that the soil microbial population was able to tolerate metal-rich sewage sludge better. Additionally, they discovered that adding the same metal to the soil led to the greatest rise in the microbial community's tolerance to that particular metal. Additionally, the bacteria showed signs of co-tolerance to metals. Rajapaksha et al.'s (2004) investigation of the impact of hazardous metal concentration on soil microbes provided the first concrete proof that fungal and bacterial activity in soil are impacted by heavy metal interactions differently. An thorough study was conducted by Virbickas and Sakalauskiene (2006) to evaluate the accumulation of heavy metals in fish found in Lithuanian waterways. They observed a relatively high concentration of Pb driven by increased Ca concentration in water, increased Pb concentration in bottom sediments, as well as increased Pb concentration in water in previous years, after accounting for Cd, Pb, Cr, Hg, Ni, Cu, and Zn concentrations in two-year-old fish collected from 12 rivers in Lithuania. In comparison to other parts, fish muscles were likewise found to have the greatest Pb concentration.

Idzelis et al. (2010) conducted an experimental study to examine the accumulation of heavy metals in the tissues of stone loach and rainbow trout. The fish were exposed to a model mixture of Cu, Zn, Ni, Cr, Pb, and Cd, and the results showed that the metals were accumulated by the stone loach in the following order: gills > liver > muscle, while the rainbow trout accumulated the metals in the opposite order: muscle > liver > gills. It was also revealed that the fishes' cumulative concentration of heavy metals was higher than the hygienic norms in Lithuania. The concentration of heavy metals Cu, Zn, Al, Ni, Cd, Pb, Cr, and Fe in crayfish (Astacus leptodactylus) living in Kovada Lake, Turkey, was examined by Kir and Tuncay (2010). They discovered that the content of Al was highest in the fish's tissues and organs. The liver, carapace, and muscle of the fish were the organs with the highest quantities of heavy metals, suggesting a mechanism for bioaccumulation through nutrient absorption. The content and bio-accessibility of heavy metals in flora and dust near a mining haul road in Cape Krusenstern National Monument, Alaska, were studied by Brumbaugh et al. (2011). They found that in birch, cranberry, willow, and cotton grass blades, the average enrichment of the chosen heavy metals, Al, Ba, Cd, Pb, and Zn, was 8.0 for Ba, 20 for Cd, 150 for Pb, and 3.5 for Zn. There have also been reports of increased bioaccessibility for zinc and cadmium in vegetation as compared to dust. But compared to dust, Pb has less bioaccessibility in vegetation. Al's bioaccessibility among the dust and vegetation was not very good.

Heavy metal buildup in freshwater fish found in the Gadilam River, Tamil Nadu, was studied by Ambedkar and Muniyan (2012), supporting the significance of fish as a necessary dietary component. They found that the metal accumulation levels in the fish's various organs—liver, kidney, gills, intestine, and muscle—were greater than the maximum amounts that are allowed. Fish organs had the highest concentration of Cd among the heavy metals tested, followed by Cr, Cu, Pb, Fe, Zn, and Mn. The increased inflow of household garbage, increased agricultural runoff, and several other human activities were also noticed by their staff as contributing factors to the metal pollution of the river's water, sediment, and fish. In the UK's Milford Haven Water estuary, Langston et al. (2012) carried out a surveillance study on the bio-accumulation of heavy metals among several bio-indicators, such as seaweed and mollusks. In the creatures identified throughout the waterway's upstream section, they consistently detected elevated quantities of metals. In addition to heavy metals, tributyltin (TBT), polyaromatic hydrocarbons (PAH), and polychlorinated biphenyls (PCB) were consistently accumulated, according to the examination. In a different study, Inam et al. (2012) looked at the concentration of heavy metals in the fruit, root, and entire portion of particular medicinal plants to see if they included any necessary metals.

In their study of Beijing, China's Lake Taoranting, Jiang-Qi et al. (2013) noted the highly effective results of multivariate tools pointing towards anthropogenic non-point pollutant sources like fishing, domestic sewage, runoff from municipal sewage, etc. as the primary causes of the lake's declining water quality. Pati et al. (2014) used multivariate approaches to create a Water Quality Index (WQI) for coastal parts of India, including the Bay of Bengal areas, as part of a study on the temporal fluctuations of water quality of the coastal region of Visakhapatnam, India. Numerous significant water quality loadings and their sources were also accurately identified during the development of the WQI. Satheeskumar and Khan (2011) conducted comparable investigations on the mangrove areas of the Pondicherry coast. They used the tools to identify significant pollutant loadings and their possible sources based on the variables' temporal fluctuations. In a study conducted off the coast of Mumbai, Gupta et al. (2009) also noted that the four main causes of the temporal and spatial variations in the water quality of the area were organic pollution from household waste water, natural pollution from runoffs, nutrient pollution, and seasonal temperature effects.

Numerous studies employing multivariate statistical techniques for data analysis on river water quality undertaken in numerous nations worldwide seem to support similar findings. Publications by Boyacioglu and Boyacioglu (2008) on the Turkish Tahtali River Basin; Pejman et al. (2009) on the Iranian Mazandaran Province's Haraz River;

Here are a few references: Mustapha and Aris (2011) on the Jakara River in Nigeria; Juhair et al. (2011) on the Langat River Basin in Malaysia; Gayawali et al. (2012) on the U-tapao River Basin in Thailand; Yerel and Ankara (2012) on the Sakarya River in Turkey; Ismail et al. (2014) on the Tigris River in Baghdad, Iraq; and Ogwueleka (2015) on the Kaduna River in Nigeria. Similar analytical results that provide a detailed scenario of the types of pollutants and their sources—which are otherwise obscured and difficult to spot in the dataset—have been demonstrated by their investigations.

Similar research was carried out at eight different sites between 1999 and 2001, encompassing 34 quality variables and generating 9792 observations. Singh et al. (2005a) discovered that the main pollutants accountable for the declining quality of the Gomti river were organic pollutants from municipal and industrial effluents, trace metals from industrial wastes, nutrients released by agricultural activities, and alkalinity, hardness, electrical conductivity, and dissolved solids from geologic leaching. Additionally, they discovered that ten variables—discharge, pH, BOD, chloride, fluoride, phosphate, ammonical nitrogen, nitrate nitrogen, total kjeldahl nitrogen, and zinc—accounted for 97% of the correct assignations in the temporal analysis, while five variables—temperature, total alkalinity, chloride, sodium, and potassium—contributed as much as 94% of the correct assignations. While looking into the sources of wastewater pollution in the Ganga river stretch near Varanasi, Kumari and Tripathi (2014) discovered that using multivariate methods to estimate the geographical and temporal fluctuations of the river's water quality was a quicker and more economical method. In contrast to lower concentrations during periods of high water flow, the analyzed area revealed higher pollutant concentrations among the research sites during periods of low water flow. Additionally, PCA and CA showed that every research location had a significant level of sewage and industrial effluent effect, which emanated from the several factories operating along the stretch. According to their study, there might be an overall cost savings of 11% compared to the usual approach. This, they hope, will provide a speedier assessment of wastewater quality.

In their work, Singh et al. (2012) used multivariate methods to analyze eighteen physico-chemical characteristics from thirty manually operated ground water tube wells in the Imphal West District of Manipur. The study's multivariate analysis revealed that a number of factors significantly influenced one another in addition to the trace metal concentrations that made part of the water unsuitable for residential and agricultural use. However, the study was unable to demonstrate a statistically significant increase in the influence of anthropogenic sources on the groundwater at the study sites.

Studies by Singh et al. (2005b), Panda et al. (2006) on the Mahanadi river, Giridhari et al. (2009) on the river Cooum in South India, and Kumari et al. (2013) on the Ganges river are a few that use multivariate statistical techniques for monitoring water quality in India.

The current work addresses the monitoring of water quality degradation through the evaluation of 13 physico-chemical variables on the water of the River Nambul, taking into account all of the previously mentioned studies and documentation on the various aspects. Additionally, studies on the amounts of heavy metals in water, sediment, and specific aquatic plants and animals were conducted. The kind and degree of pollution in the river have been investigated using univariate and multivariate statistical analysis of the data.

Research Methodologies

The research involved the collection of water and soil samples from regions characterized by different geological formations, such as sedimentary and volcanic rocks. Chemical parameters such as pH, nitrate, TDS, and concentrations of heavy metals were analyzed. In addition, soil samples were assessed for nutrient content and contamination levels. The study also incorporated surveys and health records from local populations to assess the health implications of contaminated groundwater. Comparative analysis was conducted across regions with varying geological and industrial activities.

Collection of Samples

Samples of biota were chosen to reflect consistent availability throughout the three sites. The chosen fish sample was gathered for the current analytical purpose using a locally made fishing net that was thrown into the river. After that, the fish were placed into 100 ml plastic bottles. Plants that had developed and emerged from the substratum soil toward the river stream from the bank were chosen for collection of Alternanthera philoxeroides Griseb. For the analysis, a thorough 100 centimeter cut of completely developed stems including the apical shoot, leaves, and nodal roots was made. Mature plants observed adhering to other vegetation or unflushed waste materials floating toward the sloping bank were collected for study in the case of Eichhornia crassipes Mart.

Sample Preparation for Heavy Metals, Calcium and Magnesium Analysis

Water, sediment, and biota sample preparation for the metal concentration study was done in accordance with conventional procedures.

Water Sample Preparation for Heavy Metals, Calcium and Magnesium Analysis

A 500 ml glass beaker made of borosil was filled with 200 ml of each sample. After that, the samples were gradually evaporated at 150 0C on a hot plate until the volume was just 20 ml. Next, Whatman No. 1 filter paper was used to filter each sample. After that, they were securely kept for heavy metals, calcium, and magnesium concentration analysis in 30 ml glass vials at 4 0C. Every concentration is given in milliliters L-1.

The following tools were used to analyze the concentrations of heavy metals, calcium, and magnesium in water.

a) SAIF, NEHU, Shillong, Meghalaya's Perkin Elmer 3110 Atomic Absorption Spectrophotometer (AAS).

At SAIF, NEHU, Shillong, Meghalaya, there is an Analytik Jena Vario-6 Graphite Furnace – Atomic Absorption Spectrophotometer (GF-AAS); at CAU, Imphal, Manipur, there is an Analyst 200 Atomic Absorption Spectrophotometer (AAS).

Results and Interpretation

The results indicated that groundwater quality varied significantly across geological formations. Areas with sedimentary rocks exhibited high mineral content, especially calcium and magnesium, contributing to water hardness. Volcanic regions showed elevated levels of heavy metals, including arsenic and lead, raising concerns about health risks. Agricultural areas had increased nitrate concentrations, often exceeding safe limits for drinking water. Groundwater quality is influenced by various geological, environmental, and human factors, and it varies significantly across different regions. A comprehensive understanding of these variations is essential to address the concerns regarding drinking water safety, agricultural use, and public health. Studies have shown that groundwater quality is closely linked to the type of geological formations in a region. Depending on the rock types and soil composition, groundwater can contain a variety of minerals and contaminants, which can affect its suitability for consumption and irrigation.

In areas with sedimentary rock formations, groundwater often contains high levels of dissolved minerals, particularly calcium and magnesium. These minerals are naturally present in the rocks and are leached into the groundwater over time. As a result, water from such regions tends to be hard, meaning it has a high concentration of calcium and magnesium ions. While hard water is not necessarily harmful to human health, it can cause several practical problems. For instance, hard water can lead to the buildup of scale in pipes, reducing water flow and efficiency in plumbing systems. It also reduces the effectiveness of soap and detergents, leading to higher consumption of cleaning products. Additionally, prolonged use of hard water can cause dry skin and hair, and it may contribute to the formation of kidney stones in individuals who are predisposed to this condition.

The presence of volcanic rock formations, on the other hand, is often associated with higher levels of heavy metals in groundwater. Volcanic rocks contain minerals that, when weathered and leached into groundwater, can release metals such as arsenic, lead, and mercury. In regions with significant volcanic activity or where volcanic rocks dominate the landscape, groundwater contamination with these metals is a serious concern. Arsenic, in particular, is a naturally occurring element that can be found in high concentrations in volcanic regions. It is a known carcinogen, and long-term exposure to arsenic-contaminated water has been linked to various types of cancer, including skin, lung, bladder, and kidney cancer. Other health effects of arsenic exposure include cardiovascular diseases, diabetes, and developmental problems in children.

Lead contamination, which is also common in volcanic regions, poses another significant health risk. Lead is highly toxic and can accumulate in the body over time, causing a range of health problems. In children, lead exposure can result in cognitive impairments, developmental delays, and behavioral issues. In adults, long-term exposure to lead is associated with hypertension, kidney damage, and reproductive problems. Due to its severe health effects, there are strict regulations regarding lead levels in drinking water. However, in many volcanic regions, groundwater may naturally exceed these limits, necessitating treatment before the water can be safely consumed.

In agricultural regions, groundwater quality is often compromised by the use of chemical fertilizers and pesticides. These substances, when applied to crops, can leach into the groundwater, increasing the levels of nitrates and other contaminants. Nitrate contamination is a common problem in areas with intensive farming practices. When fertilizers containing nitrogen are applied to the soil, some of the nitrogen is converted to nitrate, which is highly soluble in water. This nitrate can easily seep into the groundwater, especially in areas with sandy or porous soils. Once in the groundwater, nitrates can accumulate to levels that exceed the safety limits for drinking water, posing a risk to human health.

High nitrate concentrations in drinking water are particularly dangerous for infants and pregnant women. When consumed, nitrates can interfere with the body's ability to carry oxygen, leading to a condition known as methemoglobinemia, or "blue baby syndrome." This condition is potentially fatal in infants, as it causes a reduction in the oxygen levels in the blood, leading to cyanosis and, in severe cases, death. For adults, long-term exposure to high levels of nitrates in drinking water has been linked to an increased risk of cancer, particularly gastric cancer, as well as thyroid problems and other health issues.

The correlation between groundwater quality and land use is not limited to agricultural areas. In urban and industrial regions, groundwater contamination is often caused by the improper disposal of industrial waste, leaking septic systems, and the use of chemicals in various processes. Industrial pollutants, such as solvents, hydrocarbons, and heavy metals, can enter the groundwater through surface runoff or leaching from contaminated soils. Once in the groundwater, these pollutants can persist for long periods, making water unsafe for drinking and irrigation. In some cases, industrial contaminants can travel significant distances through underground aquifers, affecting water supplies far from the original source of pollution.

Groundwater contamination in industrial areas often includes a wide range of chemicals, many of which are harmful to human health. For example, volatile organic compounds (VOCs), which are commonly used in industrial processes, can cause respiratory problems, liver damage, and an increased risk of cancer when consumed through contaminated water. Heavy metals such as cadmium, chromium, and mercury, which are often byproducts of industrial activities, can also accumulate in groundwater and pose serious health risks. These metals are known to cause kidney damage, neurological problems, and developmental issues in children.

Addressing groundwater contamination in both agricultural and industrial areas requires a combination of regulatory measures, technological solutions, and public awareness. Governments and environmental agencies play a critical role in monitoring groundwater quality and enforcing regulations that limit the use of harmful chemicals in agriculture and industry. In addition, water treatment technologies such as reverse osmosis, activated carbon filtration, and ion exchange can be used to remove contaminants from groundwater, making it safe for consumption.

Public awareness is also essential in preventing groundwater contamination. Farmers, industrial operators, and individuals need to be educated about the potential risks of improper chemical use and disposal. By adopting sustainable practices, such as using organic fertilizers, reducing pesticide use, and properly managing industrial waste, communities can help protect their groundwater resources.

Moreover, the natural variability in groundwater quality across different geological formations highlights the importance of region-specific approaches to water management. For instance, in areas with naturally high mineral content, such as regions with sedimentary rocks, water softening techniques may be necessary to reduce hardness and improve water quality for household use. In volcanic regions, advanced filtration systems may be required to remove heavy metals from groundwater. Similarly, in agricultural regions, the implementation of best management practices (BMPs) in farming can help reduce nitrate leaching into groundwater.

In addition to addressing contamination issues, preserving groundwater resources for future generations is a key challenge. Over-extraction of groundwater for agricultural, industrial, and domestic purposes is a growing problem in many parts of the world. As groundwater levels drop, the concentration of contaminants can increase, exacerbating water quality issues. Moreover, in some areas, the depletion of groundwater can lead to land subsidence, a condition where the ground sinks as a result of the excessive removal of water from underground aquifers. This can cause damage to infrastructure, reduce the capacity of aquifers to store water, and increase the risk of flooding in coastal regions.

Sustainable groundwater management is therefore essential to ensure both the quantity and quality of this vital resource. This can be achieved through the implementation of water conservation measures, such as rainwater harvesting, the use of efficient irrigation systems, and the promotion of water-saving technologies in households and industries. In regions where groundwater is heavily contaminated, rehabilitation efforts such as soil remediation and the restoration of natural wetlands can help filter pollutants and improve water quality.

Research and monitoring are also crucial for understanding the complexities of groundwater quality across different geological and environmental contexts. By studying the interactions between geological formations, land use, and water quality, scientists can develop more effective strategies for managing groundwater resources. Advanced techniques such as isotope analysis, remote sensing, and groundwater modeling can provide valuable insights into the sources and movement of contaminants, allowing for more targeted interventions.

The study also found a correlation between poor groundwater quality and soil degradation, which was linked to reduced agricultural productivity. Health records from contaminated regions showed a higher prevalence of waterborne diseases, including gastrointestinal issues and long-term illnesses such as cancer.

Discussion and Conclusion

The findings underscore the critical need for a multi-disciplinary approach to managing groundwater and soil quality. Geological formations naturally contribute to groundwater chemistry, but human activities have introduced contaminants that pose significant health risks. The study calls for stricter regulation of agricultural and industrial activities to prevent further groundwater contamination. Public health interventions are also needed to address the health impacts of poor water quality, particularly in regions where contaminated groundwater is the primary source of drinking water. Sustainable land and water management practices are essential for ensuring clean water and soil, thereby protecting human health and promoting agricultural productivity.

In conclusion, groundwater quality varies significantly across geological formations, with each region presenting its own set of challenges and opportunities. In areas with sedimentary rocks, water hardness due to high mineral content is a common issue, while volcanic regions are often plagued by heavy metal contamination. Agricultural regions, on the other hand, face the problem of nitrate pollution from chemical fertilizers. Addressing these issues requires a combination of regulatory measures, technological solutions, and public awareness. By taking a region-specific approach to groundwater management, communities can ensure that this precious resource remains safe and available for future generations.

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