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Impacts of Agricultural Practices on Groundwater Quality and its Retrieval Methods and Solutions: A Critical Review

Dr. Shyamal S. Virnodkar[1], Sanika S. Virnodkar[2], Sunil Kumar Jha[3], Varsha P. Gaikwad[4], Dr. Sangita B. Nemade[5], Ms. Mrunali Desai[6]

[1]*Associate Professor, Department of Computer Engineering, K. J. Somaiya Institute of Technology, Sion, Mumbai, India.*
[2]*Bachelor of Technology, Department of Chemical Engineering, Bract's Vishwakarma Institute of Technology, Pune, India.*
[3]*Research Scholar, Applied Agricultural Remote Sensing Centre, University of New England, Armidale, 2351, NSW, Australia.*
[4]*Assistant Professor, Information Technology Department, Government College of Engineering, Aurangabad, Maharashtra, India.*
[5]*Assistant Professor, Computer Engineering Department, Government College of Engineering and Research, Avasari, Pune, India.*
[6]*Assistant Professor, Computer Engineering Department, K. J. Somaiya Institute of Technology, Sion, Mumbai, India.*
E-mail: shyamal@somaiya.edu

Groundwater, as a vital natural resource, plays a pivotal role in sustaining ecosystems and human activities, underscoring its indispensable significance for environmental and societal well-being. This paper critically examines the impact of agricultural practices on groundwater quality, focusing on contamination sources, retrieval methods, and future research directions. Agricultural activities, crucial for food security and economic growth, have led to significant environmental challenges, notably groundwater contamination from chemical, biological, and radioactive pollutants. Effective retrieval techniques, including advanced technologies like Geographic Information Systems (GIS), are pivotal for prompt contamination identification and mitigation. Highlighting the significant ramifications of agricultural activities on groundwater quality and the pressing need for effective mitigation strategies. Through an examination of contamination sources and retrieval methods, it underscores the urgency of addressing chemical, biological, and radioactive pollutants. As we navigate the complexities of agricultural sustainability, proactive measures and innovative solutions are essential to safeguard groundwater resources. By fostering a deeper understanding of these challenges and embracing responsible stewardship, we can strive towards sustainable resource management and environmental resilience in the face of evolving agricultural landscapes.

Keywords: Biological Contamination, Chemical Contamination, Groundwater, Radioactive Contamination.

1. Introduction

Groundwater is an essential natural resource, and the sustainability of the ecosystem and human use depend on its quality. With an emphasis on contamination sources, retrieval tactics, and future research goals, this paper provides a thorough critical analysis of the effects of agricultural activities on groundwater quality, retrieval techniques, and prospective remedies. A review is conducted on the sources of contamination resulting from agricultural activities, encompassing chemical, biological, and radioactive materials. Next, retrieval methods are covered, with an emphasis on real-time monitoring for quick contamination identification. These methods include both traditional monitoring wells and cutting-edge GIS technologies. Various potential remedies are offered for these contaminations, with an emphasis on modern water treatment technologies investigated by numerous researches, best management practices for sustainable agriculture, and conservation of soil and water. Throughout history, agriculture has been indispensable for human survival, ensuring food security and economic prosperity. Nevertheless, the intensification and expansion of agricultural practices have led to significant environmental ramifications, particularly concerning groundwater contamination.

Within the agricultural sector, numerous sources contribute to groundwater pollution, encompassing a spectrum of chemical, biological, and radioactive contaminants. Chemical pollutants originate from a multitude of sources, including fertilizers, pesticides, herbicides, and other agrochemicals extensively used to enhance crop yields and combat pests and weeds. These substances, although beneficial in enhancing agricultural productivity, pose substantial risks to groundwater quality due to their leaching potential and persistence in the soil-water environment.

Furthermore, biological contaminants, such as pathogens and microbial organisms associated with livestock farming and organic waste disposal, present additional challenges to groundwater quality management. The release of animal waste and untreated organic matter into the soil can facilitate the transport of pathogens and nutrients into groundwater reservoirs, thereby compromising its potability and ecological integrity. In addition to chemical and biological contaminants, the agricultural sector also poses risks of radioactive contamination, primarily through the utilization of phosphate fertilizers enriched with radionuclides. The presence of radionuclides in groundwater sources can pose significant health hazards, necessitating robust monitoring and mitigation strategies to safeguard human health and environmental well-being. Given the multifaceted nature of groundwater contamination associated with agricultural practices, effective retrieval methods and remediation strategies are imperative to mitigate its adverse impacts in Figure 1. However, advancements in technology, such as Geographic Information Systems (GIS) and remote sensing, offer unprecedented opportunities for real-time monitoring and spatial analysis of groundwater dynamics, facilitating prompt detection and response to contamination events.

In light of these challenges and opportunities, this paper seeks to provide a critical review of the impacts of agricultural practices on groundwater quality, elucidating the underlying mechanisms of contamination, exploring innovative retrieval methods, and outlining prospective solutions to safeguard water resources for future generations.

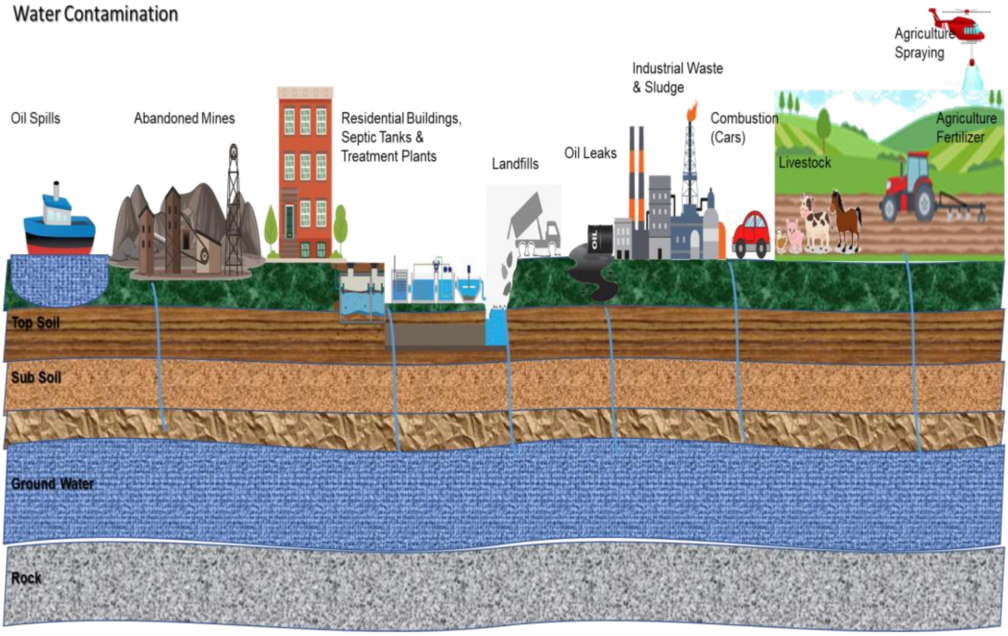

Figure 1: The water contamination system.

Water supplies can get contaminated by a wide range of hazardous substances, which poses serious dangers to both the environment and public health. The following categories include common contaminants found in drinking water:

1. Chemical Contamination

This section delves into diverse sources of chemical contamination, spanning agricultural and industrial sources. It looks at the effects that artificial compounds in farming have on the groundwater, as well as the dangers that come from industrial processes. The thorough research emphasizes how important it is to implement strong monitoring and mitigation strategies in order to handle the various issues that these toxins present in Figure 2.

Organic Contaminants: Untreated domestic and commercial waste, pesticides, and other organic contaminants could contaminate groundwater, lakes, rivers, and ponds. Organic material exposure can result in serious health issues such as cancer, neurological abnormalities, and hormone imbalances.

Inorganic contamination: can occur in drinking water (both surface and groundwater) through industrial processes, plumbing systems, and natural sources. Metals such as chromium, cyanide, copper, mercury, lead, fluoride, arsenic, and antimony are examples of inorganic contaminants. Industrial chemicals can emit dangerous substances into the air, water, and soil as a result of production operations.

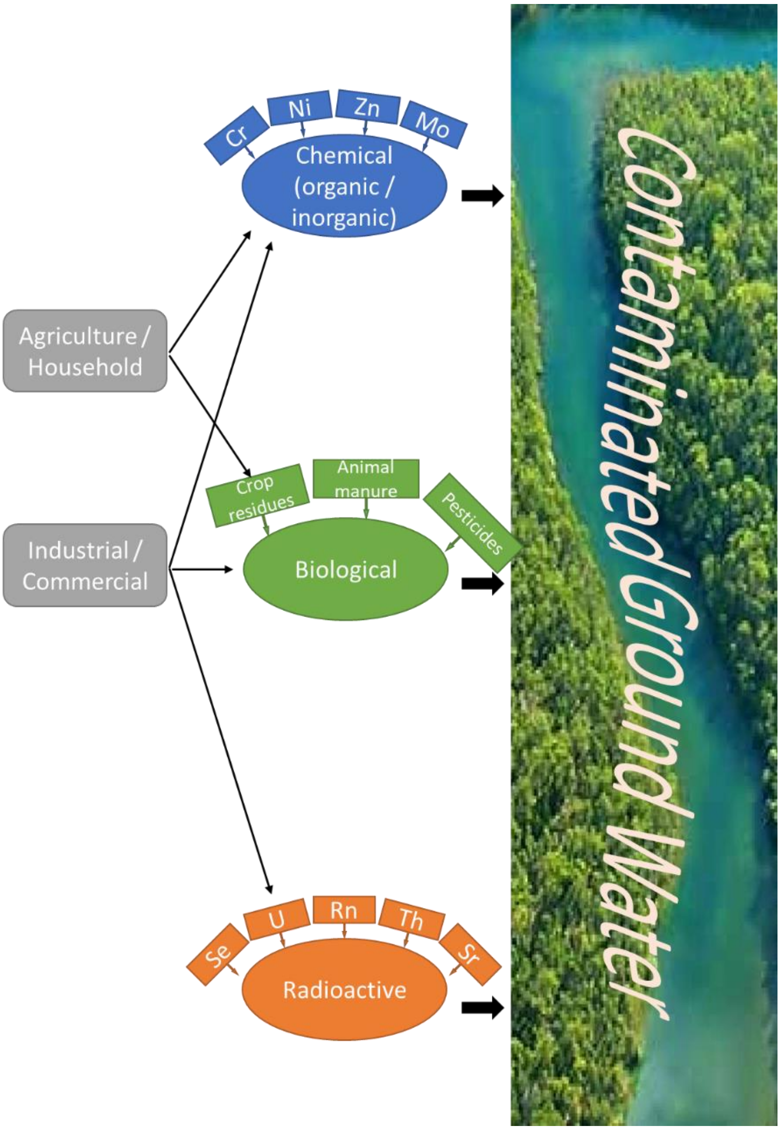

Figure 2: Types of Contamination

1.1.1 Agricultural chemicals

Agrochemicals, in the form of pesticides and fertilizers, were considered a gift to humanity. However, as studies progressed, it became evident that chemical fertilizers and pesticides cause significant harm to soil, which in turn impacts groundwater. The need to feed the world's expanding population has made modern agriculture heavily dependent on the widespread use of agrochemicals. The necessity of agrochemicals is more than ever given that by 2050, there will probably be 9.7 billion people on the planet. However, due to their inherent persistence, these agrochemicals have the potential to harm groundwater resources and soil quality. In this study, it is investigated whether the use of pesticides and fertilisers in intensive agricultural techniques to improve crop output has an effect on groundwater quality. We will include different types of pollution in this analysis, including large-scale irrigators like TPC for sugarcane plantations and small-scale irrigators like paddy rice, coffee, bananas, maize, onions, tomatoes, horticulture, and vegetables, all of which depend on groundwater for crop irrigation. Heavy metals, pesticides, major dissolved cations, and major dissolved anions were all examined in groundwater samples taken from the region. The results are helpful for future groundwater resource monitoring projects in the Pangani basin as a whole as well as for the sustainable management of the water resources in the Kahe watershed (Lwimbo et al., 2019).

In many sub-Saharan African nations, groundwater is a crucial source of water for a community's many needs. In order to deal with the lack of surface water, it serves as a better water supply in both urban and rural areas. However, it is believed that anthropogenic activities such as farming, industrial effluents, and inappropriate land-surface waste management are the primary drivers of groundwater pollution. Geological formation, soil type and permeability, precipitation levels, the aquifer's hydraulic conductivity, and the solubility of the rock components are some additional factors that impact groundwater quality.(Masindi & Foteinis, 2021).

In a former rural area of the Banat Plain, (Divya, 2012) evaluated the effects of chemical fertilisers on water quality indicators. It conducted an analysis of fertilizer residues and physico-chemical properties including pH, zinc, iron dissolved oxygen, total chloride, total dissolved solids, temperature, conductivity, total phosphate, urea, and free ammonia. The author has discovered that fertilizers used in greater amounts than necessarily have a negative effect on the physico-chemical characteristics of water, making it hazardous. Additionally, researchers discovered that as soil depth increases, fertilizer amounts in groundwater drop.

Groundwater supplies could also get contaminated as a result of pesticide use in agriculture. When organochlorine pesticides were banned in the 1960s and 1970s due to their negative effects, organophosphorus pesticides (OPs) were frequently utilized. However, OPs also lead to groundwater pollution. The (Aktar et al., 2009) study assessed the level of organophosphate pesticide contamination in the Kota region's groundwater. Their research has revealed contaminants from numerous organophosphate herbicides in the groundwater of the Kota region. For Bangladesh's, (Shahrukh, Saif, Shahid Akhtar, 2022) evaluated numerous effects of chemical fertilisers and pesticides on groundwater, soil degradation, and human health. In the study 2019 (Lwimbo et al., 2019), the effects of cultivators' heavy use of agrochemicals (fertilisers and pesticides) on the quality of groundwater in the Kahe watershed are evaluated. The results of this study offer crucial information for management of groundwater quality interventions in Tanzania's Kahe Catchment. In order to identify the sources and concentration of uranium in the groundwater of the hard rock aquifer, (Raja & Neelakantan, 2022) examined 54 groundwater samples using a GIS technique that spotlights the contaminated water quality parameters and the uranium-contaminated location using inverse distance weighted spatial interpolation plots. The agricultural use of fertilizer in the research area is the cause of this contamination. Direct consequences of agricultural runoff and groundwater recharge include changes to the hydrologic system that affect irrigation and drainage as well as the dissolution and transport of excessive amounts of fertilizers and related compounds. Changes in water-rock processes in soils and aquifers brought on by higher concentrations of dissolved oxidants, protons, and major ions are some indirect consequences. Numerous inorganic chemicals, such as NO3 -, N2, Cl, SO4 -, H+, P, C, K, Mg, Ca, Sr, Ba, Ra, and As, as well as a vast range of insecticides and other organic compounds, have been directly or indirectly impacted by agricultural activities. To distinguish shifting inputs from subsequent modifications as the drivers of concentration gradients in groundwater for reactive pollutants like NO3 -, a mix of isotopic, chemical, and environmental-tracer analytical methods are necessary. Characteristics of groundwater pollution in a growing vegetable agriculture area of a developed metropolis city was studied by (Taufiq et al., 2019) The research area's groundwater body was located in a highly reductive, saline environment. The results showed that Nitrate concentration exceeds the groundwater standard and is higher than ammonium concentration. Organic matter that is luminous in colour is mostly produced by microbial metabolism. The major complexes of Cr, Ni, Zn, and Mo are fluorescent small molecules. PFC fate and transport are influenced by both organic and inorganic chemicals.

Application of nitrogen fertilizers in the wrong quantity raises the risk of groundwater contamination. At the Dez and Karkhe rivers in the north of Khozestan-Iran, where these impacts were examined by (Mahvi et al., 2005), it was discovered that all groundwater samples had NO3 t- concentrations below the EPA MCL (44.27 mg/l) and WHO recommendation (50 mg/l). Another study by (Goudarzi et al., 2017) discovered that 9% of the Iranian aquifer's surface was contaminated with nitrate. According to a study on the temporal variability of nitrate concentrations in South Korea published in 2015, baseline-loading group median NO3-N concentrations were 5-7 mg/L with temporal variations of 5–34%, while upland wells and those close to livestock facilities had median NO3-N concentrations of 11–41 mg/L with temporal variations of 10–87% (Ki et al., 2015). Irrigation has an impact on the salinization of aquifers and soil in arid and semi-arid environments. There are two types of impacts: direct and indirect (Pulido-Bosch et al., 2018). Direct impacts arise directly from applying water and accompanying agrochemicals to farmland, whereas indirect impacts are caused by the effects of irrigation abstractions on groundwater hydro geochemistry. In GW (Rashid et al., 2023), agricultural practices also contribute to the contamination of heavy metals including Cd, Zn, and Cu. According to farming practises (irrigation rate, fertilizer application, etc.), the research study (Cabrera et al., 2024) has assessed the trace elements in deep groundwater resources [Complex Terminal (CT) and Continental Intercalaire (CI)] used for irrigation and found that the concentrations in the sampled groundwater exceed the recommended values for irrigation waters because they locally exceed these values. Long-term groundwater dynamics are impacted by intensive agricultural activities. Water over pumping also affects groundwater levels and salinity was researched by (Odeh et al., 2019) in Jordan using RS and GIS.

1.1.2 Industrial and Other Chemicals:

Besides agricultural chemicals, industrial and some other components also contribute to chemical contamination in groundwater. In many Middle Eastern and North African nations, it is common practise to reuse treated wastewater (TWW) for agriculture (MENA). Pharmaceuticals and personal care products (PPCPs) were examined by (Yalin et al., 2023) in five wastewater treatment facilities (WWTPs), groundwater, irrigated soils, and plants in the Jordanian governorates of Amman and Al-Balqa. These pharmaceutical residues could be harmful to the health of people and animals who drink the water because the treated effluents permeate and mix with the groundwater, depending on the mixing ratio. Also looking into how TWW affects groundwater, (Verlicchi et al., 2023) discovered that it encourages the spread of antibiotic resistance and that long-term TWW irrigation increased the relative abundance of sul1 and in the groundwater microbiome.(Abd-Elgawad et al., 2021) conducted an analysis of non-targeted organic compounds in the groundwater of the Assiut Governorate in Egypt to determine their chemical oxygen demand (COD) and organic composition. (Urseler et al., 2022) found atrazine in groundwater (50%) and raw bovine milk (89%) samples collected from dairy farms. Larger distances from the aquifer's recharge area showed increased salinity in the groundwater, according to their observations. The study (Twinomucunguzi et al., 2023) looked at how antibiotics were affected by on-site sanitation procedures (OSS) in shallow groundwater beneath an informal settlement in Kampala City, Uganda, and the dangers associated with antibiotic resistance as a result. (ANGMO et al., 2023) discovered chemical combination impacts on groundwater and surface water in England. Numerous contaminants, such as pathogenic bacteria, heavy metals, and resistant organic compounds, are present in landfill leachate. (Javahershenas et al., 2022) assessed the groundwater and surface water pollution levels around the Lahijan dumping site. The results showed that the seasonal river water exceeded set criteria for turbidity, BOD5, COD, EC, TDS, Mn, and Ni. PPCP causes soil and groundwater contamination, which poses serious threats to ecosystems and human health even at very low concentrations 2022 (Huang et al., 2021). Groundwater quality in a rural location impacted by abandoned pyrite ash waste dumps was evaluated (Vasilache et al., 2022). Numerous studies indicated that home and industrial wastewaters had a significant impact on the contamination of groundwater (Jan, H., & Jan, 2021). In 2022, Humnabad Srikanth found Groundwater contamination caused by heavy metals that are produced by the weathering of parent materials and should happen as a result of human activity. Farming Methods, nitrate contamination, irrigation pumping, heavy metal contamination, and uranium all have effects on groundwater. Cations and anions are examples of inorganic pollutants, and the majority of them are found naturally in rocks, sediments, and soils. Heavy metals including cadmium (Cd), chromium (Cr VI), lead (Pb), manganese (Mn), mercury (Hg), and nickel are examples of cations (Ni). After mineral breakdown in acidic waters (from mining or other industrial activity) or as a result of industrial emissions, these extremely dangerous compounds may enter the groundwater. Nitrate (NO3), nitrite (NO2), sulphate (SO4 2), fluoride (F), chloride (Cl), arsenate (AsO43), and arsenite (AsO33) are among the anions in groundwater that are of importance. High nitrate/nitrite concentrations in groundwater are caused by anthropogenic activities and naturally occurring nitrification processes, whereas SO4-2 and Cl levels are raised by seawater intrusion and rock weathering. Natural water contamination with arsenic has been discovered in Argentina, Chile, Mexico, China, Hungary, India, Bangladesh, and Vietnam.

In the Bengal Basin (India), where more than 40 million people are impacted, this contamination poses a public health risk. This groundwater is arsenic-rich, and it can only be found in reducing aquifers made of alluvium, closed basins, or poorly drained inland aquifers (Haghighizadeh et al., 2024).

1.2 Biological Contamination Sources

The organic matter produced by various human activities is the primary cause of biological contamination in rivers. This includes sewage from homes and businesses, animal and agricultural waste, food processing plants, and other sources. Some of these substances are amplified in the food chain, some can cause cancer in humans, some react with chlorine used to disinfect water to become carcinogens, some harm or even kill fish and other aquatic life, and some are simply annoyances that give fish and water an unpleasant taste or smell. Water quality is lowered and aquatic ecosystems, particularly fish, are harmed when inland waterways are acidified by sulphur and nitrogen-based acidifying agents.

Eutrophication of freshwater is another issue on a global scale. The enrichment of water with nitrogen and phosphate leads to eutrophication, which is the excessive development of phytoplankton and filamentous algae that results in increased turbidity, the creation of toxins, and diurnal fluctuations in dissolved oxygen. Although home and industrial effluents account for the majority of phosphorus emissions, agriculture also plays a role.

Organic contamination is those whose molecules contain carbon as a structural element. Solvents (such as trichloroethylene [TCE], tetrachloroethylene [PCE]), gasoline oxygenates (such as methyl-tert-butyl-ether [MTBE]), gasoline components (such as BTEX: benzene, toluene, ethylbenzene, and xylene), as well as less volatile and soluble substances like medium to highly polar compounds, are among the chemicals that frequently leach into ground (e.g., carbamazepine, sulfamethoxazole, caffeine). In addition to the parent compounds, groundwater may also contain some of the transformation byproducts that come from biological or natural breakdown processes. These metabolites can occasionally be more dangerous than the parent substances (Lopes & Bender, 1998).

Despite the fact that most experts believe that the soil complex offers some protection, it by no means completely replaces it. The most important consideration for humans while utilising water is hygiene. More than 4 million individuals perish from diseases contracted via microorganisms each year, and the majority of these deaths are brought on by water tainted with bacteria. Although there are many ways that people use water in their daily lives, the greatest risk to human life arises when there is direct contact between water and people, as in bathing areas where sewage is mixed with the water, office buildings that treat and recycle waste water from toilets for reuse, and water works that use river water as the source of their water supply. In such circumstances, cyanobacteria, pathogenic protozoa, pathogenic viruses, and pathogenic bacteria are among the microorganisms that significantly impact human health. Bacteria, parasites, and viruses that cause watery illnesses like typhoid fever, dysentery, schistosomiasis, hepatitis, polio, and cholera, are examples of biological pollution. A recent faecal contamination indication is the presence of Coliform bacteria. The only sources of pollution of this kind are human and animal waste.

In addition to receiving rainwater from pertinent catchment areas, rivers also get treated and untreated effluent as well as infiltration from landfills. Because it is exceedingly difficult and expensive to remove some pollutants, prevention is advised. Zones of protection for water sources provide the basis for a partial solution to this issue (Sasakova et al., 2018).

The main causes of groundwater pollution are things that naturally exist in ground water and the mineral environment, as well as other point and diffuse pollution sources. Therefore, before it is utilised for drinking and other domestic purposes, groundwater needs to be protected, regularly monitored, and treated.

Contamination via Radioactivity

Substances that have the potential to combine at the source with drinking water (both surface and groundwater) are known as radiological contaminants. These compounds may be created by processing industrial waste or they may be naturally occurring radioactive materials found in rocks or soil. Nuclear activity-related radioactive contamination delivers ionizing radiation that can linger in the environment, disrupting the ecosystem over time and posing a serious risk to human health.

1.3 Radioactive Contamination Sources

Radioactive waste is any contamination that emits radiation in excess of what the environment normally does. It is created as a result of unprotected mining of radioactive elements such as uranium, unsafe nuclear industrial waste disposal, the dumping of medically used radioisotopes, globally dispersed (>400) nuclear power plants, and the use of phosphate fertilisers in agriculture (International Atomic Energy Agency, 2011) as well as the use of radioactive materials in research and treatment plans by academic institutions and healthcare facilities, military applications. Since radioactive waste can stay in the environment for tens of thousands of years, disposal is incredibly challenging. Consider the 56 million gallons of radioactive waste that need to be cleaned up at the decommissioned Hanford nuclear weapons production complex in Washington; it will cost more than $100 billion and take until 2060 to complete. Toxins that have been carelessly or unintentionally emitted endanger groundwater, surface water, and marine resources. Cesium (137 Cs), strontium (90 Sr), and tritium isotopes from the industrial zone in Sosnovy Bor town, where multiple nuclear power facilities are in operation, are the principal technological radionuclides detected in groundwater samples by (Erzova et al., 2023). In order to present the environmental fate, distribution, anticipated future scenarios, and corrective actions of selenium and uranium in the Indian soil-water system (P. K. Gupta et al., 2022) studied extensive literature. According to (Miklyaev et al., 2020) analysis of the tectonic physical parameters of Mt. Beshtau, a strong seasonal radon emanation anomaly has been discovered, which is likely proof of the massif's highly permeable geology. The review provides an overview of the physicochemical characteristics of radon, their sources, the groundwater radon contamination scenario in India as well as globally, health impacts, and resident bacteria and their survival tactics (Nayak et al., 2022). The physical radon removal methods are also summarised, with a focus on the microbes-based bioremediation process and their potential combination as a future efficient radon remediation method. In the vicinity of the Rooppur Nuclear Power Plant (RNPP) sites, Bangladesh, heavy metal concentration and radionuclide levels with twenty-six (26) parameters, including major cations (K, Na, Mg, Ca) and anions (SO42, NO3), trace and heavy metals (Mn, Fe, Zn, Ni, Co, Pb, Cd, As, Hg, Cu, Li, Be, B, V, Ga, Sr, Ag, Ba. The sources, distribution, and remedial measures of radioactive contamination in ecosystems were discussed in (A. O. Adeola et al., 2022). The activity concentrations of U isotopes were examined utilising the novel U separation method developed for the alpha spectrometer.

1.4 Consequences of Contamination

Following are major areas where contamination is affected adversely,

- Human health
- Quality of lands and forests, Soil contamination
- Surface water quality
- Reducing freshwater availability

Following figure (fig. 3) shows different categories researchers have studied the groundwater contamination.

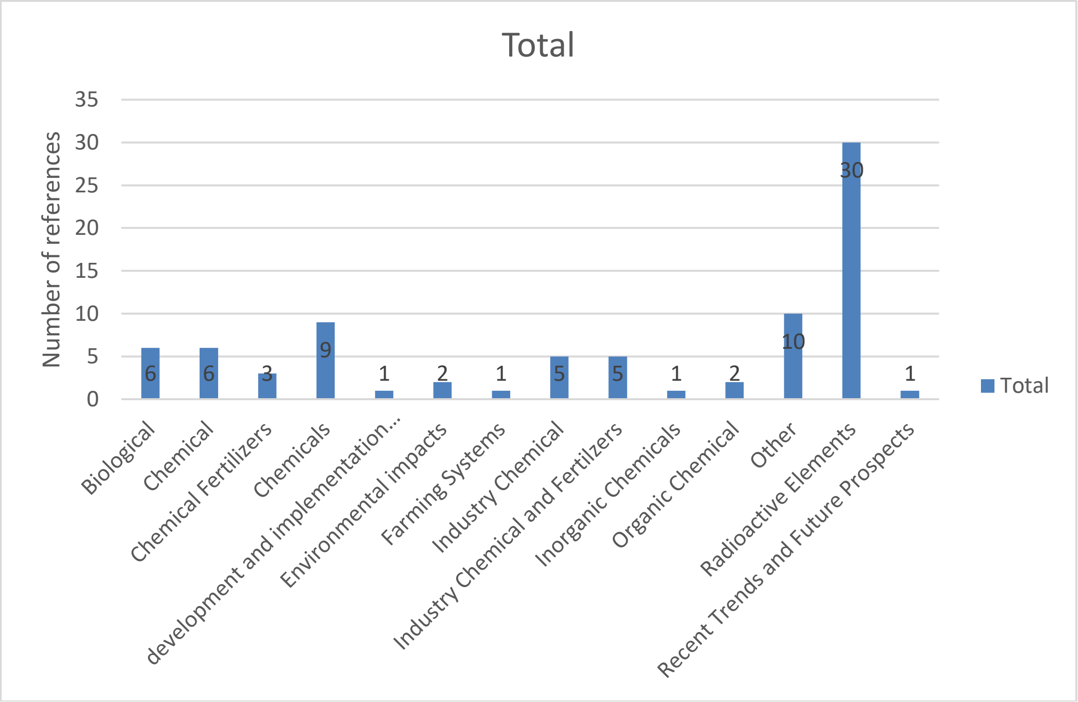

Figure 3 provides number of studies referred in different categories for groundwater contamination

2. Contamination Retrieval Methods

The assessment of physico-chemical parameters and bacterial counts used in the monitoring of ground and surface water quality in an agricultural area indicates the quality and possible pollution of water sources. Water samples from all four seasons are collected for testing. Based on the standards for the quality of water used for human consumption established by government regulation, the outcomes of ground water testing were evaluated. The condition of the surface under investigation was able to forecast the fate of nitrogen fertilisers and the transport of nitrate from the rooting zone of agricultural areas to surface water and groundwater in the Seine basin by accounting for the prolonged residence times of water and nitrate in the unsaturated and aquifer systems (Kumar et al., 2022). The geographic units are selected by the authors based on knowledge about pedological characteristics, land use, and farming practices. These data are converted into input data for the crop model STICS, which simulates the nitrogen and water balances in the soil-plant system using a daily time-step (Rahman et al., 2021).

2.1 Chemical contaminants retrieval methods

Agricultural - retrieval methods

The objectives of a study (Zalidis et al., 2002) are to: (a) highlight the distinctive qualities of the Mediterranean region; (b) highlight the major impacts of agricultural practises on soil and water calibre in light of the aforementioned characteristics; and (c) propose an easy and financially feasible methodology for the evaluation of soil quality at the scale of watersheds, from specific functional interest zones. Recognizing groundwater pollution in agricultural areas and assessing the danger of pesticide-related groundwater pollution are becoming increasingly critical 2012 (Khanna & Gupta, 2018). The four main risk evaluation methodologies are examined in the above study. Site-Specific Pollution Issues are studied by (Opaluch & Mazzotta, 1993). An index method was used to estimate groundwater danger at the national level (Elkhalki et al., 2023) in Portugal. For risk estimate and rating, integrating N hazards and aquifer vulnerability was a useful strategy. If the reduction in precipitation is significant, reducing N leaching might not lessen the danger of N contamination. The index system foresaw additional hotspots and the current risk zones.

2.2 Biological contaminants retrieval methods

Without safeguarding the water sources, it is impossible to guarantee an adequate supply of good drinkable water. In general, surface waterways account for three-fourths of the water utilised in agriculture, industry, and our houses, with the remaining one-fourth coming from groundwater. Although ground waters are not as frequently impacted by pollution as surface waters are, the effects are more severe.

The fight against contamination of water and watercourses has a long history, although solely on a local level. A UNECE (United Nations Economic Commission for Europe, 1992) Water Convention on the preservation and use of transboundary watercourses and international lakes was created in response to the increased awareness of potential issues.

This convention and its amendments are designed to increase national efforts to safeguard and manage transboundary surface waters and ground waters in an environmentally responsible manner. In accordance with the Water Convention, Parties are required to manage transboundary waters sustainably, use transboundary waters in a fair and equitable manner, and prevent, control, and mitigate their adverse effects.

Water pollution legislation is very complicated. Depending on whether a discharge is discharged into a public sewer, the maritime environment, or inland, estuary, or tidal waterways, different laws may be applicable. There are two potential control strategies:

either a maximum emission standard or the quality of the water in the receiver after the point of discharge must be specified by individual state directives.

This study examined three bacterial-based methods for differentiating human from animal fecal contamination in simulated groundwater: the ratio of fecal coliforms to fecal streptococci, antibiotic-resistant Clostridium perfringens, and human bifidobacteria. After validating each indicator's specificity on samples from known sources of pollution, it was discovered that only the concentration of human bifidobacteria could be reliably determined. This approach, however, was only successful for two weeks following contamination. Antibiotic-resistant Clostridium perfringens is not source-specific, but it can be helpful in predicting general fecal contamination occurrences, according to the study (Cimenti et al., 2005).

2.3 Radioactive contamination retrieval methods

Radioactive contamination of groundwater is a critical environmental problem that requires effective remedial methods to protect human health and ecosystems. As human activities continue to contribute to the release of radioactive materials underground, innovative and sustainable approaches are needed to mitigate the impact on groundwater resources. This section explores various search methods designed to eliminate radioactive contamination of groundwater.

In order to quickly and selectively adsorb 90Sr from groundwater, researchers at (Sihn et al., 2022) changed the ion-exchange affinity of nano-Hydroxyapatite (Ca5(PO4)3OH, HAP) surface by post-substituting cations (Al3+, Cu2+, Na+, Ba2+, Mg2+, and Fe3+) for parent Ca2+. The (002) peak of this modified HAP showed a small shift between 25° and 27° depending on the ionic radius of the substituted cation in the diffraction patterns. MnO2 fibre was used to extract 226Ra from contaminated groundwater samples based on the radium's chemical behaviour by (KHRAISHEH et al., 2004). Reverse osmosis (RO) and nanofiltration (NF) were studied for the removal of radium, Ra2 + 226, 228, uranium, as uranyl cations, UO22 +, or carbonate complexes, UO2(CO3)22, and radon, Rn222, in comparison to the most popular conventional methods of ion exchange resins (IERs), chemical precipitation/softening, coagulation. Due to its radioactivity and chemical toxicity, dissolved uranium in groundwater at high quantities poses a rising global hazard to both human and ecological health. (Gandhi et al., 2022) numerous techniques are covered in depth, including adsorption, biosorption and bioremediation, strong base anion exchange resins, advanced oxidation processes like photocatalysis, and electrocoagulation. On the basis of hydrological data made in a small number of boreholes, a method is suggested for determining the regional distribution of aquifer transmissibility. The issue can be boiled down to a minimization issue that was mathematically resolved by (Malkovsky, 2022).

Spatio-temporal estimation using GIS

In Albenga, North Italy, (Jhariya et al., 2019)pioneered the use of Pesticide DRASTIC and Susceptibility Index (SI) methodologies within a GIS framework to assess groundwater vulnerability. (Torkashvand et al., 2023) introduced a kriging-based approach, integrating modified DRASTIC and nitrate concentration for groundwater pollution risk assessment. (Matzeu et al., 2017) advanced the methodology, employing SINTACS, SI, and IPNOA to evaluate intrinsic nitrate contamination risk. Recognizing DRASTIC's limitations, Wang (2008) developed the D-DRASTIC method for nitrate contamination risk using GIS. (Matzeu et al., 2017) highlighted increased groundwater nitrate concentrations in Italy due to intensive agricultural practices. (Barroso et al., 2015) mapped groundwater susceptibility in Portugal, utilizing GIS tools. In South Portugal, T. Y. Stigter (2005) used intrinsic DRASTIC and Susceptibility Index (SI) for vulnerability mapping. (Neshat et al., 2014) emphasized standardization in DRASTIC model application. (Persaud & Levison, 2021a) used DRASTIC-AgLU-CC to predict future groundwater pollution risk. (Menderes et al., 2019) assessed groundwater pollution risk in Nebraska using GIS-based vulnerability models.

One of the main issues with groundwater management, particularly in dry areas where agriculture supports the local and regional economies, is human-caused contamination from rigorous agronomic tracts, particularly in groundwater (Dangar et al., 2021). Under these conditions, it is crucial to regularly assess the quality of the groundwater. However, it is expensive and labor-intensive to collect groundwater samples by ground inventory, particularly over large regions. AqQA and GIS software, as well as geostatistical methods, are therefore frequently used to comprehend water analysis, groundwater quality evaluation, and its sensitivity to contamination modelling. AqQA was developed by aqueous geochemists and water engineers to save chemical analysis results in a spreadsheet designed specifically to review analyses for internal consistency, graph data, etc (Haghizadeh, 2016). Many academics employ GIS and geostatistical methods far too frequently for the spatial estimate of multi-component in a variety of domains (Paramasivam, 2019). According to (Habibi Davijani et al., 2014), GIS is a new technology paradigm that has the ability to create spatial databases, while geostatistical techniques are helpful for estimating the values of unsurveyed areas. The geostatistical interpolation method produces visually pleasing maps from irregularly spaced data using geostatistical grinding operations, making it a better way for estimating and analysing groundwater samples (Xiao et al., 2016). Many fields have used interpolation techniques like kriging and Inverse Distance Weight (IDW), using the IDW interpolation method to identify spatio-temporal variation in physico-chemical data (Khouni et al., 2021).

To assess the risk of future groundwater pollution, DRASTIC-AgLU-CC is used by (Persaud & Levison, 2021b). Land use and climate variables are viewed as dynamic model inputs. On model output, the impact of complex land use schemes is evaluated. Model predictions might be enhanced by detailed depiction of agricultural land usage. Depending on how land uses are represented, different pollution risks are predicted.

In this work, the regional groundwater pollution risk in the Elkhorn River Basin, Nebraska, USA, is assessed using a groundwater vulnerability model that uses data from freely accessible national and state-wide geospatial datasets. Land use is a crucial consideration since the model, which is implemented in a geographic information system (GIS), is specifically designed to address the dangers of nitrate pollution in agricultural landscapes (Menderes et al., 2019).

In order to improve agricultural practices and lessen their environmental impact on the soil and shallow aquifer, high resolution multispectral and hyperspectral methods are being used in conjunction with data processing and geographic information systems (GIS) in place of traditional methods for evaluating land features (field analysis, measurements, and mapping). -GIS and remote sensing methods for determining the water content of the soil to enhance farming practices and lessen adverse effects on groundwater: case study, agricultural region (Tevi & Tevi, 2012).

Fig. 4 provides year wise count and fig. 5 provides publisher wise count of references explored in this study.

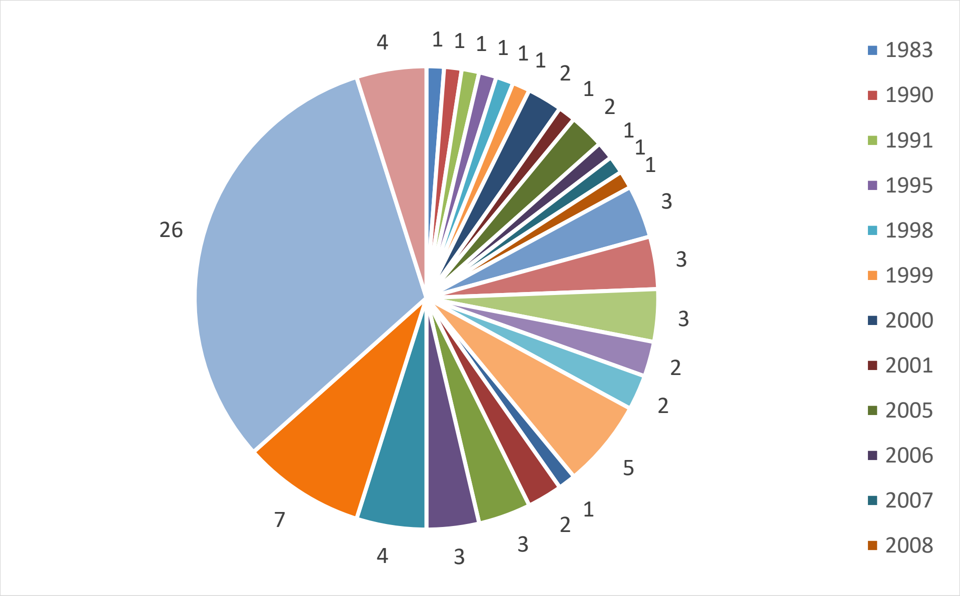

Figure 4 Year wise count of references

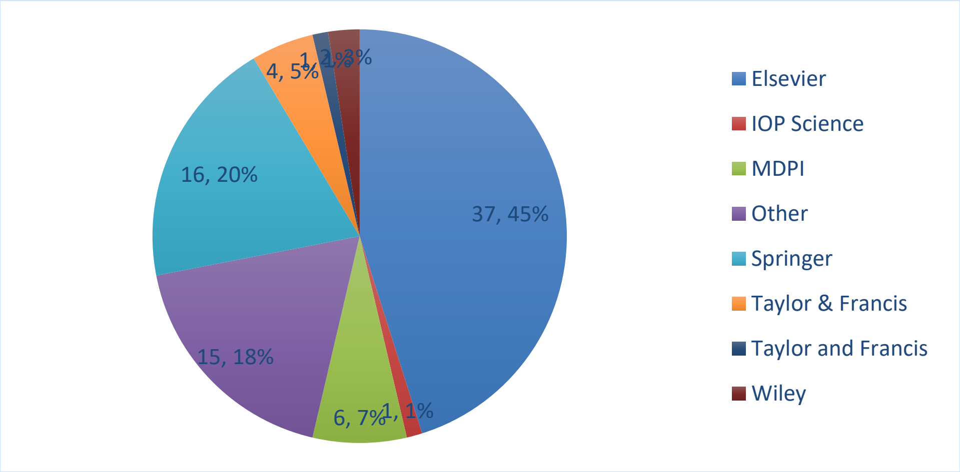

Figure 5 Publisher wise count of references

3. Solutions

3.1 Chemical contaminants solutions

The main research questions that need to be answered in order to inform the creation and implementation of policy on agricultural diffuse water pollution are outlined in this paper, which was written from the viewpoint of individuals working at the intersection of science and policy in four UK government organisations. It explains the circumstances in which policymakers might use newly discovered information to guide their decisions as well as options for utilising research outputs in the policy-making process. Also, it discusses how to address diffuse pollution through policy, including who makes decisions when and how science might help (Wiering et al., 2023). The mathematical modelling of groundwater pollution caused by agricultural practices is currently at a very high degree of development, and there are many models available for a wide range of water pollution issues. Also, a range of computational techniques, from the most basic to the most sophisticated, are available. In general, there are two ways to obtain a water quality model: "from below," in which the calculus explicitly analyses water quality data based on actual observation or measurement; and "from above," in which the calculus is already known in advance as a theory and the user attempts to determine its interpretation for a specific case and using relatively few data (Pietrzak, 2021).

The North China Plain's wheat-maize rotation has been enhanced recently, which has resulted in difficulties with the environment and biodiversity as well as a dramatic decline in the groundwater level. According to (Wang et al., 2023) research, reducing cropping density slowed the fall of the groundwater table and increased resilience while stabilising productivity and reducing negative environmental impacts. Rotations of wheat and maize with soybean, millet, and potatoes produced a number of cobenefits. High crop yields, protection for the environment's ecosystems, and prevention of groundwater contamination from these agrochemicals are all possible with the implementation of sustainable farming methods and mitigating measures. Additionally, it encourages the use of fertilisers and insecticides with biological origins by giving both traditional and local knowledge and cutting-edge farming methods equal weight (Pretty & Bharucha, 2014).

(Sajedi-Hosseini et al., 2018) proposed a new methodology for risk analysis of nitrate pollution of groundwater in dry areas. Prediction of susceptibility, pollution, and likelihood of occurrence was aimed using machine learning (ML). Rapid regional assessment of the risk presented by nitrate in groundwater is made possible using ML. The efficiency of mitigation strategies in nitrate-vulnerable zones is affected by translating the agricultural N surplus hazard into groundwater pollution risk, according (Cameira et al., 2021) attempted to provide a technique that generates an adequate indicator for the efficiency of N mitigation strategies in reducing groundwater nitrate contamination. Aquifer vulnerability and the agricultural N surplus hazard are combined to create the Global Risk Index (GRI). To determine water recharge at the municipal level, both irrigation activity and precipitation contribution are taken into account.

The study (Johnson et al., 2019) assesses the on-farm costs of ways to reduce nitrate groundwater pollution by merging plant modelling, economic, and hydrologic models of farm-level processes. Nitrate pollution is decreased with little loss of revenue by adjusting the timing and application rates of nitrogen and water. Once such methods are used, it will become increasingly expensive for growers to reduce nitrate levels.

By reducing groundwater contamination from nitrate leaching, increasing water use efficiency, and reducing water stress, improved nitrogen fertilizer use efficiency—especially through precise irrigation and fertilization technologies like spray irrigation—is considered essential for safeguarding drinking water in rural areas, especially in North China (Ju et al., 2006).

Linking agriculture and climatic scenarios is necessary for planned adaptation strategies. The sustainability of groundwater depends on a reduction in irrigated acreage and a switch in crop types. Agricultural adaptations are what need to be the emphasis of wetland preservation (Rosa, 2022).

3.2 Biological contaminants solutions

(Korbel et al., 2013) investigated how the shallow alluvial aquifer of the Gwydir River valley in New South Wales, Australia, responds to agricultural land uses. The author's evaluated the quality of the groundwater and the microbiological and stygofauna assemblages at locations with irrigated, non-irrigated, and grazed land uses. This study underscores the value of groundwater biota for biomonitoring, particularly in agricultural landscapes, and indicates notable changes in the composition of groundwater ecosystems in locations with varied surface land uses. A model is created to investigate patterns of socially advantageous agricultural shallow groundwater exploitation. Groundwater cleanup from industrial and agricultural chemicals has been accomplished through on-site biological treatment which uses reactors like trickling filters, upflow fixed-film reactors, and fluidized bed reactors (Langwaldt & Puhakka, 2000). However, this method has limitations because it requires elevated temperatures and has high operating costs. Future research on bioremediation of arsenic-contaminated soils and groundwater is highly promising, with particular emphasis on how cost- and environmentally-friendly it can be. Ex-situ bioleaching for efficient bulk arsenic removal, biostimulation to increase leaching rates, and biosorption for both ex-situ and in-situ arsenic removal were highlighted in the study (Cimenti et al., 2005) that assessed the viability of biological approaches for arsenic remediation. Introducing the right biosorbents or microorganisms is essential to the effectiveness of in-situ biosorption. The authors explored the potential development of biovolatilization as an ex-situ treatment, the use of arsenic-hyperaccumulating plants in phytoremediation, and the engineering of genetic techniques for improved hyperaccumulation. The focus of the research conducted by authors of the study is on two kinds of biological agents that can degrade xenobiotics such as polychlorinated biphenyls, benzene, toluene, and m-xylene: bacteria and plants (Demnerová et al., 2005). They also investigated how these compounds might be used to eliminate organic contaminants from a variety of environmental matrices, such as soil and water.

3.3 Radioactive contamination solutions

To remove radioactive materials from soils and water, several remediation technologies use physical (extraction, precipitation, and membrane separation technologies) and chemical (leaching, chemical extraction and hydrolysis, etc.) approaches (Singh et al., 2023). A number of mitigation techniques are used for the efficient removal of uranium from treated water, including bioremediation using biochars from various sources, nanoparticle technology, and adsorption by magnesium (Mg)-iron (Fe)-based hydrotalcite-like compounds (MF-HT). At Thu Duc District, Ho Chi Minh City, Vietnam, the proposed removal method employing K2FeO4 removed 234U and 238U, respectively, with removal rates of 74.28% and 81.04% (Van Thang et al., 2022). The (Dai et al., 2023) review presents a dynamic viewpoint on microbial regulation while summarising recent developments, mechanisms, and difficulties. They suggested a dynamic and all-encompassing groundwater N system based on microbial regulation in light of their findings. The movement and transformation patterns of the most recent N indicators, the effects of environmental change on each N component, and the not insignificant implications of these factors on the management of groundwater N contamination were also critically summarised. The article looks at the financial effects and current trends of agricultural water contamination. The OECD's recent policy experiences in managing water pollution in agriculture together with the medium-term outlook for pollution in all OECD nations are presented (Parris, 2011). (A. Gupta et al., 2022) investigates the mechanisms of managing agricultural shallow groundwater extraction in a socially desirable manner. It becomes evident that the existing groundwater price is ineffective and offers less motivation for the adoption of cutting-edge irrigation technology than one that includes the cost of desiccation and groundwater contamination. In order to better understand the condition of groundwater contamination and potential dangers to local inhabitants in an alluvial plain (China) where agricultural and industrial activities are intense, an evaluation of groundwater quality was conducted (Wu & Sun, 2016). For evaluating the quality of irrigation water, sodium adsorption ratio, Na%, and residual sodium carbonate were employed, while the Comprehensive Water Quality Index was utilized for evaluating the quality of drinking water. Nitrate Surface water quality is also harmed by groundwater contamination. Increases in ground water NO3-N have been linked to significant increases in N-fertilization, according to research conducted globally. The acceptable NO3-N drinking water requirements are currently exceeded by many shallow groundwater supplies. While there are several sources of N that enter the environment, synthetic fertilisers now make up the majority of it. One important step in solving these issues is to spread the ideas of sustainable, alternative agriculture (Laney & Johnson, 2021). Agricultural practices affect groundwater NO3 pollution in an area that is irrigated by the Yellow River. The research area's shallow groundwater and ineffective NO3 and water management techniques are leaving a lasting legacy of contamination (Chen et al., 2010). Nitrate concentrations in the groundwater of sandy soils and agricultural field surpluses of nitrogen are both high in the Netherlands (Oenema et al., 1998). In order to reduce nitrogen losses to acceptable levels, the Dutch government implemented a number of policies and programmes beginning in 1986. The nitrogen and phosphorus accounting system MINAS, which will be used starting in 1998, is the primary emphasis. Using whole-farm analysis and simulation models, with a primary focus on nitrate leaky sandy soils and dairy farming systems, the potential effects of the MINAS policy and policies on the nitrate contamination of groundwater have been investigated. Determination of nitrate leaching into the shallow groundwater system during the cultivation of maize and soybeans were conducted using two tillage methods: chisel plough (CP) and no till (NT) with liquid swine manure treatment (Nila Rekha et al., 2011). This study is a component of long-term field experiments with entirely random block designs carried out at Iowa State University. Three depths were used to monitor the NO3-N concentrations in the shallow ground water: 1.2 m for a network of subsurface drains, and 1.8 m and 2.4 m for piezometers. The average NO3-N concentration during the study period was 16.1 mg l1, 14.4 mg l1, and 11.8 mg l1, respectively, at 1.2 m, 1.8 m, and 2.4 m depths, indicating significant NO3-N leaching past the subsurface drain depth of 1.2 m into the shallow groundwater, though the NO3-N concentration decreases with depth. Simulations of nitrate leaching-related aquifer contamination on a wide scale are presented in the research by (Nila Rekha et al., 2011).

In order to pinpoint pollution sources and transformation processes in the soils and shallow groundwater of a rural area in Korea with significant agricultural activity, the hydro-geochemistry of groundwater's major constituents and stable isotope ratios of NO3 and SO42 were determined (Kaown et al., 2009). Three different organic amendments—a municipal solid waste compost (MSWC), as well as aerobically (AES) and anaerobically (ANS) digested sewage sludge— were looked at to become leachable inorganic nitrogen forms (NH4+-N and NO3-N) over the course of two years in an agricultural soil, and how solutes moved through the vadose zone in a Mediterranean climate by (Jorge-Mardomingo et al., 2015). These waters in Morocco are vulnerable to contamination from the nearby agricultural activities due to the nature of the soil and the extent of the water table at a shallow depth. For this collected samples of three agricultural sandy soils and conducted physicochemical analyses on them to determine the pH, water content, bulk density, electrical conductivity (EC), organic matter (OM), cation exchange capacity (CEC), and soil grain size distribution. To ascertain the amounts of major and trace elements in the fine fraction (FF) of the soils, inductively coupled plasma-optical emission spectrometry (ICP/OES) was used. The soils' elemental makeup was then determined by X-ray powder diffraction (XRD) and measured by X-ray fluorescence (XRF) (Sarti et al., 2022).

2. Conclusion

In conclusion, this comprehensive review synthesizes a wealth of research findings on groundwater contamination originating from diverse sources, namely agriculture, industry, and household activities, with a particular emphasis on chemical, biological, and radioactive elements. The literature review highlights the complexity of the problem and the necessity for tailored and sophisticated remedial approaches. Precision farming and optimal irrigation techniques are necessary to address chemical contaminants, which are mostly caused by agricultural operations. Because industries play a major role in groundwater contaminants, strict regulations and cutting-edge treatment methods must be put in place. Household sources, while small on their own, represent a significant threat when combined, hence better waste management and awareness campaigns are required. Because biological contamination is frequently linked to human activity, novel bioremediation strategies and ecosystem-based interventions are needed. Strong monitoring and remediation plans that take into account both the short- and long-term effects are crucial given the possible risks connected to radioactive materials. The interplay of multidisciplinary research, technological developments, and policy interventions becomes increasingly important as we navigate the complexities of groundwater contamination. This is because it guarantees sustainable water quality and protects human and environmental well-being in the face of expanding global challenges.

Research Directions

According to (Adeola et al., 2023) future research should concentrate on cost-effectiveness, waste minimization, sustainability, and quick radioactive decontamination even though comprehensive radionuclide decontamination using the various technologies is technically feasible. For effective and long-lasting uranium removal from groundwater, future research must concentrate on creating hybrid and cutting-edge methods (Gandhi et al., 2022). In Telangana, India, a dryland watershed, seeks to comprehend the effect of intensive agricultural practices on the accessibility of water resources. For sustainable agricultural production in dryland areas, it is necessary to promote agro-ecologically sound farming methods, enhance the available technical choices, and implement new regulations (Kuchimanchi et al., 2023). Planning with several objectives to create an ideal cropping pattern and artificial recharge system for the best possible use of surface and groundwater resources (Salehi Shafa et al., 2023). Land use and hydrology interaction affects the quantity and composition of dissolved organic matter (DOM) in groundwaters and stream water through time in an agricultural watershed. The findings of imply that vegetative buffers may not be as effective at preventing DOM leakage as cultivated uplands in agricultural lands employing animal waste as fertilizer. Farming Methods and Hydrologic Conditions Determine the Temporal Pattern of Organic Matter Dissolved in Soil and Stream Water (Liu et al., 2023). Sorting farming methods according to how they affect the quality of groundwater implementation of a multi-criteria analysis in order to respond to a query from INRA researchers that evaluate the effects of agricultural practices on environmental elements (Arondel & Girardin, 2000). They were especially interested in differentiating cropping systems (CSs) based on how such systems affected the quality of groundwater. The connection between groundwater and surface water was examined using stable isotopes. The study region is in an area of Egypt with a dry climate. According to (Mittal et al., 2020), the research area is subject to intensive year-round agricultural operations. In a nutshell following are the various future directions for the researchers:

Emerging Contaminants:

As more and more contaminants are found in groundwater, including industrial chemicals, pharmaceuticals, and personal care items, research remains focused on finding and decreasing their adverse effects.

Biological Remediation Methods:

Researching and creating bioremediation methods for groundwater contaminated with heavy metals and organic contaminants. Investigating the use of microbes to degrade or immobilize pollutants is part of this.

Processes of Natural Attenuation:

Researching the attenuation mechanisms that occur naturally to learn how pollutants change or become less harmful with time in the absence of human interference is needed. This entails investigating elements such as hydrological conditions, geochemical processes, and microbial activity.

Surface Water-Groundwater Interactions:

Recognizing the intricate relationships that exist between surface water and groundwater, particularly in areas where both systems are intertwined. In order to control contamination and preserve the quality of the water in both systems, this is essential.

Applications of Nanotechnology:

Looking at how nanotechnology might be used to clean up groundwater. The potential of nanomaterials and nanoparticles to absorb or change pollutants in situ is being investigated.

Modeling and Risk Assessment:

Developing modeling methods and risk assessment approaches to forecast the fate and flow of pollutants in groundwater. This entails creating risk management plans and refining predictive models to comprehend the movement of contaminants.

Climate Change's Effects:

Evaluating how climate change may affect precipitation patterns, temperature, and extreme weather events, all of which may have an impact on the transit and destiny of contaminants in groundwater.

Technologies for Observation:

Advancing the identification and tracking of pollutants in groundwater by creating and deploying cutting-edge monitoring technologies such sensor networks, remote sensing, and real-time monitoring.

Frameworks for regulations and policies:

Examining and suggesting modifications to legal and regulatory structures in order to more effectively handle and avoid groundwater pollution. This includes updating environmental legislation to reflect recent scientific discoveries.

Radioactive Contamination:

Investigate efficient techniques for cleaning up radioactively contaminated groundwater by investigating microbiological, precipitation, and ion exchange technologies.

References

1. Abd-Elgawad, A., Seleem, E., Zeid, S., & Salman, S. (2021). Organic compounds residues investigation in groundwater at Assiut governorate, Egypt. Egyptian Journal of Chemistry, 0–0. https://doi.org/10.21608/ejchem.2021.96028.4503
2. Adeola, A. O., Iwuozor, K. O., Akpomie, K. G., Adegoke, K. A., Oyedotun, K. O., Ighalo, J. O., Amaku, J. F., Olisah, C., & Conradie, J. (2023). Advances in the management of radioactive wastes and radionuclide contamination in environmental compartments: a review. Environmental Geochemistry and Health, 45(6), 2663–2689. https://doi.org/10.1007/s10653-022-01378-7
3. Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. Interdisciplinary Toxicology. https://doi.org/10.2478/v10102-009-0001-7

4. ANGMO, S., Kharayat, Y., & Shah, S. (2023). Assessment of Contamination Potential in Okhla Landfill, New Delhi by using Leachate Pollution Index. Current World Environment, 18(1), 116–132. https://doi.org/10.12944/CWE.18.1.11
5. Arondel, C., & Girardin, P. (2000). Sorting cropping systems on the basis of their impact on groundwater quality. European Journal of Operational Research, 127(3), 467–482. https://doi.org/10.1016/S0377-2217(99)00437-3
6. Barroso, M. F., Ramalhosa, M. J., Olhero, A., Antão, M. C., Pina, M. F., Guimarães, L., Teixeira, J., Afonso, M. J., Delerue-Matos, C., & Chaminé, H. I. (2015). Assessment of groundwater contamination in an agricultural peri-urban area (NW Portugal): an integrated approach. Environmental Earth Sciences. https://doi.org/10.1007/s12665-014-3297-3
7. Cabrera, A., Cendón, D. I., Aparicio, V., & Currell, M. J. (2024). Intensive agriculture, a pesticide pathway to >100 m deep groundwater below dryland agriculture, Cordoba Pampas, Argentina. Journal of Hydrology, 643, 131989. https://doi.org/10.1016/j.jhydrol.2024.131989
8. Cameira, M. do R., Rolim, J., Valente, F., Mesquita, M., Dragosits, U., & Cordovil, C. M. d. S. (2021). Translating the agricultural N surplus hazard into groundwater pollution risk: Implications for effectiveness of mitigation measures in nitrate vulnerable zones. Agriculture, Ecosystems & Environment, 306, 107204. https://doi.org/10.1016/j.agee.2020.107204
9. Chen, S., Wu, W., Hu, K., & Li, W. (2010). The effects of land use change and irrigation water resource on nitrate contamination in shallow groundwater at county scale. Ecological Complexity, 7(2), 131–138. https://doi.org/10.1016/j.ecocom.2010.03.003
10. Cimenti, M., Biswas, N., Bewtra, J. K., & Hubberstey, A. (2005). Evaluation of microbial indicators for the determination of bacterial groundwater contamination sources. Water, Air, and Soil Pollution. https://doi.org/10.1007/s11270-005-0961-y
11. Dai, H., Zhang, Y., Fang, W., Liu, J., Hong, J., Zou, C., & Zhang, J. (2023). Microbial community structural response to variations in physicochemical features of different aquifers. Frontiers in Microbiology, 14. https://doi.org/10.3389/fmicb.2023.1025964
12. Dangar, S., Asoka, A., & Mishra, V. (2021). Causes and implications of groundwater depletion in India: A review. Journal of Hydrology, 596, 126103. https://doi.org/10.1016/j.jhydrol.2021.126103
13. Demnerová, K., Mackova, M., Speváková, V., Beranova, K., Kochánková, L., Lovecká, P., Ryslavá, E., & Macek, T. (2005). Two approaches to biological decontamination of ground-water and soil polluted by aromatics-characterization of microbial populations. International Microbiology, 8(3), 205–211.
14. Divya. (2012). Impact of chemical fertilizers on water quality in selected agricultural areas of Mysore district, Karnataka, India. International Journal of Environmental Sciences. https://doi.org/10.6088/ijes.00202030030
15. Elkhalki, S., Hamed, R., Jodeh, S., Ghalit, M., Elbarghmi, R., Azzaoui, K., Hanbali, G., Ben Zhir, K., Ait Taleb, B., Zarrouk, A., & Lamhamdi, A. (2023). Study of the quality index of groundwater (GWQI) and its use for irrigation purposes using the techniques of the geographic information system (GIS) of the plain Nekor-Ghiss (Morocco). Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1179283
16. Erzova, V. A., Rumynin, V. G., Nikulenkov, A. M., Vladimirov, K. V., Sudarikov, S. M., & Vilkina, M. V. (2023). Forecast of radionuclide migration in groundwater of the zone affected by construction drainage at the Leningrad NPP-2. Journal of Mining Institute, 260, 194–211. https://doi.org/10.31897/PMI.2022.27
17. Gandhi, T. P., Sampath, P. V., & Maliyekkal, S. M. (2022). A critical review of uranium contamination in groundwater: Treatment and sludge disposal. Science of The Total Environment, 825, 153947. https://doi.org/10.1016/j.scitotenv.2022.153947
18. Goudarzi, S., Jozi, S. A., Monavari, S. M., Karbasi, A., & Hasani, A. H. (2017). Assessment of

groundwater vulnerability to nitrate pollution caused by agricultural practices. Water Quality Research Journal, 52(1), 64–77. https://doi.org/10.2166/wqrjc.2017.031

19. Gupta, A., Singh, R. kumar, Kumar, M., Sawant, C. P., & Gaikwad, B. B. (2022). On-farm irrigation water management in India: Challenges and research gaps*. Irrigation and Drainage, 71(1), 3–22. https://doi.org/10.1002/ird.2637
20. Gupta, P. K., Saxena, G., & Yadav, B. (2022). Selenium and naturally occurring radioactive contaminants in soil–water systems. In Advances in Remediation Techniques for Polluted Soils and Groundwater (pp. 259–267). Elsevier. https://doi.org/10.1016/B978-0-12-823830-1.00020-1
21. Habibi Davijani, M., Nadjafzadeh Anvar, A., & Banihabib, M. E. (2014). Locating Water Desalination Facilities for Municipal Drinking Water Based on Qualitative and Quantitative Characteristics of Groundwater in Iran’s Desert Regions. Water Resources Management, 28(10), 3341–3353. https://doi.org/10.1007/s11269-014-0682-3
22. Haghighizadeh, A., Rajabi, O., Nezarat, A., Hajyani, Z., Haghmohammadi, M., Hedayatikhah, S., Asl, S. D., & Aghababai Beni, A. (2024). Comprehensive analysis of heavy metal soil contamination in mining Environments: Impacts, monitoring Techniques, and remediation strategies. Arabian Journal of Chemistry, 17(6), 105777. https://doi.org/10.1016/j.arabjc.2024.105777
23. Haghizadeh, A. (2016). Assessment and Mapping of Groundwater Quality Using the GIS Combining with AqQA model (Case study: Kamyaran Pline). April.
24. Huang, J., Chen, H., Zheng, Y., Yang, Y., Zhang, Y., & Gao, B. (2021). Microplastic pollution in soils and groundwater: Characteristics, analytical methods and impacts. Chemical Engineering Journal, 425, 131870. https://doi.org/10.1016/j.cej.2021.131870
25. International Atomic Energy Agency. (2011). Radioactive Waste Management Objectives. IAEA Nuclear Energy Series, 18(5), 32. http://www.iaea.org/Publications/index.html
26. Jan, H., & Jan, H. A. (2021). Impact of Industrial Effluents Discharge on Ground Water Quality. July.
27. Javahershenas, M., Nabizadeh, R., Alimohammadi, M., & Mahvi, A. H. (2022). The effects of Lahijan landfill leachate on the quality of surface and groundwater resources. International Journal of Environmental Analytical Chemistry, 102(2), 558–574. https://doi.org/10.1080/03067319.2020.1724984
28. Jhariya, D. C., Kumar, T., Pandey, H. K., Kumar, S., Kumar, D., Gautam, A. K., Baghel, V. S., & Kishore, N. (2019). Assessment of groundwater vulnerability to pollution by modified DRASTIC model and analytic hierarchy process. Environmental Earth Sciences. https://doi.org/10.1007/s12665-019-8608-2
29. Johnson, S. L., Adams, R. M., & Perry, G. M. (2019). The On-Farm Costs of Reducing Groundwater Pollution. In The Economics of Water Quality. https://doi.org/10.2307/1242434
30. Jorge-Mardomingo, I., Jiménez-Hernández, M. E., Moreno, L., de la Losa, A., de la Cruz, M. T., & Casermeiro, M. Á. (2015). Application of high doses of organic amendments in a Mediterranean agricultural soil: An approach for assessing the risk of groundwater contamination. CATENA, 131, 74–83. https://doi.org/10.1016/j.catena.2015.03.013
31. Ju, X. T., Kou, C. L., Zhang, F. S., & Christie, P. (2006). Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. Environmental Pollution, 143(1), 117–125. https://doi.org/10.1016/j.envpol.2005.11.005
32. Kaown, D., Koh, D.-C., Mayer, B., & Lee, K.-K. (2009). Identification of nitrate and sulfate sources in groundwater using dual stable isotope approaches for an agricultural area with different land use (Chuncheon, mid-eastern Korea). Agriculture, Ecosystems & Environment, 132(3–4), 223–231. https://doi.org/10.1016/j.agee.2009.04.004
33. Khanna, R., & Gupta, S. (2018). Agrochemicals as a potential cause of ground water pollution: A review Technical SCIENCE View project Black Wheat: A Health Promising Crop View

project. International Journal of Chemical Studies, January 2018, 985–990. https://www.researchgate.net/publication/350874038

34. Khouni, I., Louhichi, G., & Ghrabi, A. (2021). Use of GIS based Inverse Distance Weighted interpolation to assess surface water quality: Case of Wadi El Bey, Tunisia. Environmental Technology & Innovation, 24, 101892. https://doi.org/10.1016/j.eti.2021.101892
35. KHRAISHEH, M., ALDEGS, Y., & MCMINN, W. (2004). Remediation of wastewater containing heavy metals using raw and modified diatomite. Chemical Engineering Journal, 99(2), 177–184. https://doi.org/10.1016/j.cej.2003.11.029
36. Ki, M.-G., Koh, D.-C., Yoon, H., & Kim, H. (2015). Temporal variability of nitrate concentration in groundwater affected by intensive agricultural activities in a rural area of Hongseong, South Korea. Environmental Earth Sciences, 74(7), 6147–6161. https://doi.org/10.1007/s12665-015-4637-7
37. Korbel, K. L., Hancock, P. J., Serov, P., Lim, R. P., & Hose, G. C. (2013). Groundwater Ecosystems Vary with Land Use across a Mixed Agricultural Landscape. Journal of Environmental Quality. https://doi.org/10.2134/jeq2012.0018
38. Kuchimanchi, B. R., Ripoll-Bosch, R., Steenstra, F. A., Thomas, R., & Oosting, S. J. (2023). The impact of intensive farming systems on groundwater availability in dryland environments: A watershed level study from Telangana, India. Current Research in Environmental Sustainability. https://doi.org/10.1016/j.crsust.2022.100198
39. Kumar, L., Deitch, M. J., Tunio, I. A., Kumar, A., Memon, S. A., Williams, L., Tagar, U., Kumari, R., & Basheer, S. (2022). Assessment of physicochemical parameters in groundwater quality of desert area (Tharparkar) of Pakistan. Case Studies in Chemical and Environmental Engineering, 6, 100232. https://doi.org/10.1016/j.cscee.2022.100232
40. Laney, K., & Johnson, A. (2021). Reducing the Health Impacts of the Nitrogen Problem: Proceedings of a Workshop in Brief (2021). Reducing the Health Impacts of the Nitrogen Problem: Proceedings of a Workshop in Brief, September, 1–12. https://doi.org/10.17226/26328
41. Langwaldt, J. H., & Puhakka, J. A. (2000). On-site biological remediation of contaminated groundwater: A review. Environmental Pollution. https://doi.org/10.1016/S0269-7491(99)00137-2
42. Liu, D., Jiang, X., Duan, M., Yu, S., & Bai, Y. (2023). Human and natural activities regulate organic matter transport in Chinese rivers. Water Research, 245, 120622. https://doi.org/10.1016/j.watres.2023.120622
43. Lopes, T. J., & Bender, D. A. (1998). Nonpoint sources of volatile organic compounds in urban areas—relative importance of land surfaces and air. Environmental Pollution, 101(2), 221–230. https://doi.org/10.1016/S0269-7491(98)00048-7
44. Lwimbo, Z. D., Komakech, H. C., & Muzuka, A. N. (2019). Impacts of Emerging Agricultural Practices on Groundwater Quality in Kahe Catchment, Tanzania. Water, 11(11), 2263. https://doi.org/10.3390/w11112263
45. Mahvi, A. H., Nouri, J., Babaei, A. A., & Nabizadeh, R. (2005). Agricultural activities impact on groundwater nitrate pollution. International Journal of Environmental Science and Technology, 2(1), 41–47. https://doi.org/10.1007/BF03325856
46. Malkovsky, V. I. (2022). Calibration of Hydrodynamic Models of Groundwater Flow in Aquifers Polluted by Liquid Radioactive Waste. Processes, 10(5), 810. https://doi.org/10.3390/pr10050810
47. Masindi, V., & Foteinis, S. (2021). Groundwater contamination in sub-Saharan Africa: Implications for groundwater protection in developing countries. Cleaner Engineering and Technology. https://doi.org/10.1016/j.clet.2020.100038
48. Matzeu, A., Secci, R., & Uras, G. (2017). Methodological approach to assessment of groundwater contamination risk in an agricultural area. Agricultural Water Management.

https://doi.org/10.1016/j.agwat.2017.01.003

49. Menderes, A., Enst, M., Anab, L. E. R., Ul, D., Yunus, H., Polat, C., Dani, T. E. Z., Do, M., Roth, W. D., Cristea, A., Schulz, N. D., Witcher, B. J., Serdar, D., بارانی, س. ن. ع. س. و. ح.., Husada, F. R. K., Ninla Elmawati Falabiba, Glosny, M., Users, I. T. O., Bremmer, I., … Fei John, F. (2019). Groundwater pollution risk assessment under scenarios of climate and land use change in the northern Great Plains. Journal of Game Theory.
50. Miklyaev, P. S., Petrova, T. B., Marennyy, A. M., Shchitov, D. ., Sidyakin, P. A., Murzabekov, M. A., & Lopatin, M. N. (2020). High seasonal variations of the radon exhalation from soil surface in the fault zones (Baikal and North Caucasus regions). Journal of Environmental Radioactivity, 219, 106271. https://doi.org/10.1016/j.jenvrad.2020.106271
51. Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook. Frontiers in Nanotechnology, 2. https://doi.org/10.3389/fnano.2020.579954
52. Nayak, T., Basak, S., Deb, A., & Dhal, P. K. (2022). A systematic review on groundwater radon distribution with human health consequences and probable mitigation strategy. Journal of Environmental Radioactivity, 247, 106852. https://doi.org/10.1016/j.jenvrad.2022.106852
53. Neshat, A., Pradhan, B., Pirasteh, S., & Shafri, H. Z. M. (2014). Estimating groundwater vulnerability to pollution using a modified DRASTIC model in the Kerman agricultural area, Iran. Environmental Earth Sciences. https://doi.org/10.1007/s12665-013-2690-7
54. Nila Rekha, P., Kanwar, R. S., Nayak, A. K., Hoang, C. K., & Pederson, C. H. (2011). Nitrate leaching to shallow groundwater systems from agricultural fields with different management practices. Journal of Environmental Monitoring. https://doi.org/10.1039/c1em10120j
55. Odeh, T., Mohammad, A. H., Hussein, H., Ismail, M., & Almomani, T. (2019). Over-pumping of groundwater in Irbid governorate, northern Jordan: a conceptual model to analyze the effects of urbanization and agricultural activities on groundwater levels and salinity. Environmental Earth Sciences, 78(1), 40. https://doi.org/10.1007/s12665-018-8031-0
56. Oenema, O., Boers, P. C. M., van Eerdt, M. M., Fraters, B., van der Meer, H. G., Roest, C. W. J., Schröder, J. J., & Willems, W. J. (1998). Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in the Netherlands. Environmental Pollution, 102(1), 471–478. https://doi.org/10.1016/S0269-7491(98)80071-7
57. Opaluch, J. J., & Mazzotta, M. J. (1993). Fundamental Issues in Benefit Transfer and Natural Resource Damage Assessment.
58. Paramasivam, C. R. (2019). Merits and Demerits of GIS and Geostatistical Techniques. In GIS and Geostatistical Techniques for Groundwater Science (pp. 17–21). Elsevier. https://doi.org/10.1016/B978-0-12-815413-7.00002-X
59. Parris, K. (2011). Impact of Agriculture on Water Pollution in OECD Countries: Recent Trends and Future Prospects. International Journal of Water Resources Development, 27(1), 33–52. https://doi.org/10.1080/07900627.2010.531898
60. Persaud, E., & Levison, J. (2021a). Impacts of changing watershed conditions in the assessment of future groundwater contamination risk. Journal of Hydrology. https://doi.org/10.1016/j.jhydrol.2021.127142
61. Persaud, E., & Levison, J. (2021b). Impacts of changing watershed conditions in the assessment of future groundwater contamination risk. Journal of Hydrology, 603, 127142. https://doi.org/10.1016/j.jhydrol.2021.127142
62. Pietrzak, D. (2021). Modeling migration of organic pollutants in groundwater — Review of available software. Environmental Modelling & Software, 144, 105145. https://doi.org/10.1016/j.envsoft.2021.105145
63. Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. Annals of Botany, 114(8), 1571–1596. https://doi.org/10.1093/aob/mcu205
64. Pulido-Bosch, A., Rigol-Sanchez, J. P., Vallejos, A., Andreu, J. M., Ceron, J. C., Molina-

Sanchez, L., & Sola, F. (2018). Impacts of agricultural irrigation on groundwater salinity. Environmental Earth Sciences, 77(5). https://doi.org/10.1007/s12665-018-7386-6

65. Rahman, A., Jahanara, I., & Jolly, Y. N. (2021). Assessment of physicochemical properties of water and their seasonal variation in an urban river in Bangladesh. Water Science and Engineering, 14(2), 139–148. https://doi.org/10.1016/j.wse.2021.06.006
66. Raja, V., & Neelakantan, M. A. (2022). Application of GIS technique to address the uranium contamination in groundwater of a hard rock aquifer, South India. Geocarto International, 37(27), 18716–18730. https://doi.org/10.1080/10106049.2022.2143911
67. Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., Lehnhoff, E. A., & Beck, L. (2023). Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health. Agronomy, 13(6), 1521. https://doi.org/10.3390/agronomy13061521
68. Rosa, L. (2022). Adapting agriculture to climate change via sustainable irrigation: biophysical potentials and feedbacks. Environmental Research Letters, 17(6), 063008. https://doi.org/10.1088/1748-9326/ac7408
69. Sajedi-Hosseini, F., Malekian, A., Choubin, B., Rahmati, O., Cipullo, S., Coulon, F., & Pradhan, B. (2018). A novel machine learning-based approach for the risk assessment of nitrate groundwater contamination. Science of The Total Environment, 644, 954–962. https://doi.org/10.1016/j.scitotenv.2018.07.054
70. Salehi Shafa, N., Babazadeh, H., Aghayari, F., & Saremi, A. (2023). Multi-objective planning for optimal exploitation of surface and groundwater resources through development of an optimized cropping pattern and artificial recharge system. Ain Shams Engineering Journal, 14(2), 101847. https://doi.org/10.1016/j.asej.2022.101847
71. Sarti, O., El Mansouri, F., Otal, E., Morillo, J., Ouassini, A., Brigui, J., & Saidi, M. (2022). Assessing the Effect of Intensive Agriculture and Sandy Soil Properties on Groundwater Contamination by Nitrate and Potential Improvement Using Olive Pomace Biomass Slag (OPBS). C, 9(1), 1. https://doi.org/10.3390/c9010001
72. Sasakova, N., Gregova, G., Takacova, D., Mojzisova, J., Papajova, I., Venglovsky, J., Szaboova, T., & Kovacova, S. (2018). Pollution of Surface and Ground Water by Sources Related to Agricultural Activities. Frontiers in Sustainable Food Systems, 2. https://doi.org/10.3389/fsufs.2018.00042
73. Shahrukh, Saif, Shahid Akhtar, M. E. (2022). Health Problems of Traffic Police Personnel Due to Air Pollution. BPAjournal, January. https://www.researchgate.net/publication/357536561_Health_Problems_of_Traffic_Police_Personnel_Due_to_Air_Pollution
74. Sihn, Y., Yang, H.-M., Park, C. W., Yoon, I.-H., & Kim, I. (2022). Post-substitution of magnesium at CaI of nano-hydroxyapatite surface for highly efficient and selective removal of radioactive 90Sr from groundwater. Chemosphere, 295, 133874. https://doi.org/10.1016/j.chemosphere.2022.133874
75. Singh, G., Bhadange, S., Bhawna, F., Shewale, P., Dahiya, R., Aggarwal, A., Manju, F., & Arya, S. K. (2023). Phytoremediation of radioactive elements, possibilities and challenges: special focus on agricultural aspects. In International Journal of Phytoremediation. https://doi.org/10.1080/15226514.2022.2043239
76. State, O., Chemistry, I., Chemistry, I., & Africa, S. (n.d.). 7 8 9 *.
77. Taufiq, A., Effendi, A. J., Iskandar, I., Hosono, T., & Hutasoit, L. M. (2019). Controlling factors and driving mechanisms of nitrate contamination in groundwater system of Bandung Basin, Indonesia, deduced by combined use of stable isotope ratios, CFC age dating, and socioeconomic parameters. Water Research, 148, 292–305. https://doi.org/10.1016/j.watres.2018.10.049
78. Tevi, G., & Tevi, A. (2012). Remote sensing and GIS techniques for assessment of the soil water content in order to improve agricultural practice and reduce the negative impact on

groundwater: case study, agricultural area Ştefan cel Mare, Călăraşi County. Water Science and Technology, 66(3), 580–587. https://doi.org/10.2166/wst.2012.209

79. Torkashvand, M., Neshat, A., Javadi, S., Yousefi, H., & Berndtsson, R. (2023). Groundwater Vulnerability to Nitrate Contamination from Fertilizers Using Modified DRASTIC Frameworks. Water, 15(17), 3134. https://doi.org/10.3390/w15173134
80. Twinomucunguzi, F. R. B., Nyenje, P. M., Semiyaga, S., Kebirungi, P., Kulabako, R. N., & Kansiime, F. (2023). Antibiotics in shallow groundwater underlying urban informal settlements in developing countries: influence of on-site sanitation practices and risk assessment. Urban Water Journal, 20(10), 1731–1743. https://doi.org/10.1080/1573062X.2022.2059688
81. Urseler, N., Bachetti, R., Biolé, F., Morgante, V., & Morgante, C. (2022). Atrazine pollution in groundwater and raw bovine milk: Water quality, bioaccumulation and human risk assessment. Science of The Total Environment, 852, 158498. https://doi.org/10.1016/j.scitotenv.2022.158498
82. Van Thang, N., Thu, H. N. P., & Hao, L. C. (2022). Uranium isotopes in groundwater in Ho Chi Minh City and related issues: Health risks, environmental effects, and mitigation methods. Journal of Contaminant Hydrology, 245, 103941. https://doi.org/10.1016/j.jconhyd.2021.103941
83. Vasilache, N., Diacu, E., Modrogan, C., Chiriac, F. L., Paun, I. C., Tenea, A. G., Pirvu, F., & Vasile, G. G. (2022). Groundwater Quality Affected by the Pyrite Ash Waste and Fertilizers in Valea Calugareasca, Romania. Water (Switzerland). https://doi.org/10.3390/w14132022
84. Verlicchi, P., Grillini, V., Lacasa, E., Archer, E., Krzeminski, P., Gomes, A. I., Vilar, V. J. P., Rodrigo, M. A., Gäbler, J., & Schäfer, L. (2023). Selection of indicator contaminants of emerging concern when reusing reclaimed water for irrigation — A proposed methodology. Science of The Total Environment, 873, 162359. https://doi.org/10.1016/j.scitotenv.2023.162359
85. Wang, S., Xiong, J., Yang, B., Yang, X., Du, T., Steenhuis, T. S., Siddique, K. H. M., & Kang, S. (2023). Diversified crop rotations reduce groundwater use and enhance system resilience. Agricultural Water Management, 276, 108067. https://doi.org/10.1016/j.agwat.2022.108067
86. Wiering, M., Kirschke, S., & Akif, N. U. (2023). Addressing diffuse water pollution from agriculture: Do governance structures matter for the nature of measures taken? Journal of Environmental Management, 332, 117329. https://doi.org/10.1016/j.jenvman.2023.117329
87. Wu, J., & Sun, Z. (2016). Evaluation of Shallow Groundwater Contamination and Associated Human Health Risk in an Alluvial Plain Impacted by Agricultural and Industrial Activities, Mid-west China. Exposure and Health, 8(3), 311–329. https://doi.org/10.1007/s12403-015-0170-x
88. Xiao, Y., Gu, X., Yin, S., Shao, J., Cui, Y., Zhang, Q., & Niu, Y. (2016). Geostatistical interpolation model selection based on ArcGIS and spatio-temporal variability analysis of groundwater level in piedmont plains, northwest China. SpringerPlus, 5(1), 425. https://doi.org/10.1186/s40064-016-2073-0
89. Yalin, D., Craddock, H. A., Assouline, S., Ben Mordechay, E., Ben-Gal, A., Bernstein, N., Chaudhry, R. M., Chefetz, B., Fatta-Kassinos, D., Gawlik, B. M., Hamilton, K. A., Khalifa, L., Kisekka, I., Klapp, I., Korach-Rechtman, H., Kurtzman, D., Levy, G. J., Maffettone, R., Malato, S., … Cytryn, E. (2023). Mitigating risks and maximizing sustainability of treated wastewater reuse for irrigation. Water Research X, 21, 100203. https://doi.org/10.1016/j.wroa.2023.100203
90. Zalidis, G., Stamatiadis, S., Takavakoglou, V., Eskridge, K., & Misopolinos, N. (2002). Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agriculture, Ecosystems & Environment, 88(2), 137–146. https://doi.org/10.1016/S0167-8809(01)00249-3