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Climate Change and Groundwater Contamination: A Comprehensive Review of Impacts, Challenges and Adaptation Strategies

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تغير المناخ وتلوث المياه الجوفية: مراجعة شاملة للتأثيرات والتحديات واستراتيجيات التكيف

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Abstract

Groundwater is a hidden water reservoir, but it supports drinking water, agriculture, and public health. Climate change is now changing the pathways of groundwater restoration and groundwater contamination. The survey explains how temperature rise, changes in rainfall, droughts, sea level rise, and floods affect groundwater quality. The main impacts include salt intake, nitrate entry, arsenic emission, microbial transport, and chemical packaging. This paper uses peer-reviewed studies and general data on intergovernmental issues related to climate change, UNESCO, the World Health Organization, the U.S. Geological Survey, NASA Grace, the Environmental Protection Agency (EPA), and the World Bank. Evidence suggests that the weather rarely works alone. It operates in the fields of pumping, land use, sanitation, and groundwater geology. Public figures show clear pressures in several sectors. GRACE data showed a groundwater loss of about 109 km³ in northwest India during 2002 to 2008. The Tigris-Euphrates-western Iran region lost about 143.6 km³ total water between 2003 and 2009. A study of U.S. nitrates used 293,775 notes from 2001 to 2020. It found that rainfall and temperature influence the annual change in nitrates in 75.2% of the counties. In Bangladesh, multiple hazard maps showed that 5% to 24% of groundwater faces an overall higher risk of groundwater. This risk includes depletion of arsenic, salinity and storage. Adaptation should link climate policy with groundwater conservation. The major initiatives include monitoring, source control, well protection, safe cleaning, carefully managed aquifer recharge, shore pumping limits, and open data systems. This paper supports risk-based geogovernance for hot and less stable climates.

Keywords: Climate Change, Groundwater Contamination, Nitrates, Arsenic, Salinity Infiltration, Microbials, Depletion of Water Bodies, Systematic Water Recharge, Adaptation, General Data.

الملخص.

تمثل المياه الجوفية خزانًا مائيًا خفيًا، إلا أنها تؤدي دورًا أساسيًا في توفير مياه الشرب، ودعم الزراعة، وحماية الصحة العامة. ويؤثر تغير المناخ في الوقت الحاضر في مسارات تغذية المياه الجوفية وانتقال الملوثات إليها. وتوضح هذه المراجعة كيفية تأثير ارتفاع درجات الحرارة، والتغيرات في أنماط هطول الأمطار، وحالات الجفاف، وارتفاع مستوى سطح البحر، والفيضانات في جودة المياه الجوفية.

وتشمل أهم التأثيرات تداخل المياه المالحة، وتسرب النترات، وانطلاق الزرنيخ، وانتقال الملوثات الميكروبية، وتحرك الملوثات الكيميائية. وتعتمد هذه الورقة على دراسات خضعت لمراجعة علمية محكّمة، إضافة إلى بيانات عامة صادرة عن الهيئة الحكومية الدولية المعنية بتغير المناخ، ومنظمة الأمم المتحدة للتربية والعلم والثقافة «اليونسكو»، ومنظمة الصحة العالمية، وهيئة المسح الجيولوجي الأمريكية، ومهمة قياس الجاذبية واستعادة المناخ التابعة لوكالة ناسا«GRACE» ، ووكالة حماية البيئة الأمريكية، والبنك الدولي.

وتشير الأدلة إلى أن العوامل المناخية نادرًا ما تعمل بصورة منفردة، بل تتفاعل مع عمليات ضخ المياه الجوفية، واستخدامات الأراضي، وأنظمة الصرف الصحي، والخصائص الجيولوجية للخزانات الجوفية. وتُظهر البيانات المنشورة وجود ضغوط واضحة في عدد من المناطق. فقد أظهرت بيانات مهمة GRACE فقدان نحو 109 كيلومترات مكعبة من المياه الجوفية في شمال غرب الهند خلال الفترة من عام 2002 إلى عام 2008. كما فقدت منطقة دجلة والفرات وغرب إيران نحو 143.6 كيلومترًا مكعبًا من إجمالي مخزون المياه خلال الفترة من عام 2003 إلى عام 2009.

واعتمدت إحدى الدراسات المتعلقة بالنترات في الولايات المتحدة على 293,775 سجلًا جُمعت خلال الفترة من عام 2001 إلى عام 2020. ووجدت الدراسة أن هطول الأمطار ودرجات الحرارة يؤثران في التغير السنوي لتركيزات النترات في 75.2% من المقاطعات. وفي بنغلاديش، أظهرت خرائط المخاطر المتعددة أن ما بين 5% و24% من المياه الجوفية يواجه مستوى مرتفعًا من المخاطر المركبة. وتشمل هذه المخاطر نضوب المياه الجوفية، والتلوث بالزرنيخ، وزيادة الملوحة، وتراجع القدرة التخزينية للخزانات الجوفية.

وينبغي أن تربط استراتيجيات التكيف بين سياسات المناخ والمحافظة على المياه الجوفية. وتشمل أهم التدابير المقترحة إنشاء أنظمة للرصد والمتابعة، والسيطرة على مصادر التلوث، وحماية الآبار، وتوفير خدمات الصرف الصحي الآمن، وتنفيذ عمليات التغذية الاصطناعية المُدارة للخزانات الجوفية بعناية، وفرض قيود على ضخ المياه في المناطق الساحلية، وإنشاء نظم مفتوحة لإتاحة البيانات.

وتدعم هذه الورقة تبني نهج للحوكمة الجيومائية قائم على تقييم المخاطر، ولا سيما في المناطق الحارة والمناطق التي تشهد تقلبات مناخية متزايدة.

الكلمات المفتاحية: : تغير المناخ، تلوث المياه الجوفية، النترات، الزرنيخ، تداخل المياه المالحة، الملوثات الميكروبية، نضوب الخزانات المائية، التغذية الاصطناعية المُدارة للخزانات الجوفية، التكيف، البيانات العامة.

1.Introduction

Groundwater is located below the surface, but it is part of everyday life. It provides water for homes, farms, industry and ecosystems. Many rural areas depend on wells as their primary source of water. Many cities also use groundwater during droughts.

Climate change is now putting pressure on this hidden water system. The rains are becoming less stable at many places. Heavy rainfall is increasing in many areas. Droughts are also becoming severe or prolonged in many areas where water is scarce. Sea levels rise on many beaches. These changes affect the quantity and quality of groundwater (Intergovernmental Panel on Climate Change, 2022; UNESCO, 2022; Lamma, 2021b).

The quality issue is often more difficult than the quantity problem. The dry well can be changed occasionally. The contaminated layer can remain unprotected for many years. Pollution slowly passes through several water bodies. Some contaminants persist for decades in sediments and water holes. This delay makes early prevention very important (Mohammad et al., 2015b).

Climate change does not produce all pollution. It alters the movement and response of pollutants. Heavy rains can push nitrates, bacteria, pesticides and salts into shallow water. (Lamma, 2021a; Lamma & Swamy, 2018) Drought can reduce pollution and increase the amount of pollution. Strong pumping contaminants can draw shallow water into deep supply areas. Rising sea levels can carry salt water inland. Hot groundwater can alter oxidation, compacting, and mineral reaction conditions (Dow, 2024; USGS, 2022).

This review examines these links in a clear framework. Defines important weather paths. It reviews general practical data and published studies. It also offers adaptation methods that can reduce groundwater contamination in the future. The paper uses simple language and direct evidence. This book is written for students, researchers, and water administrators.

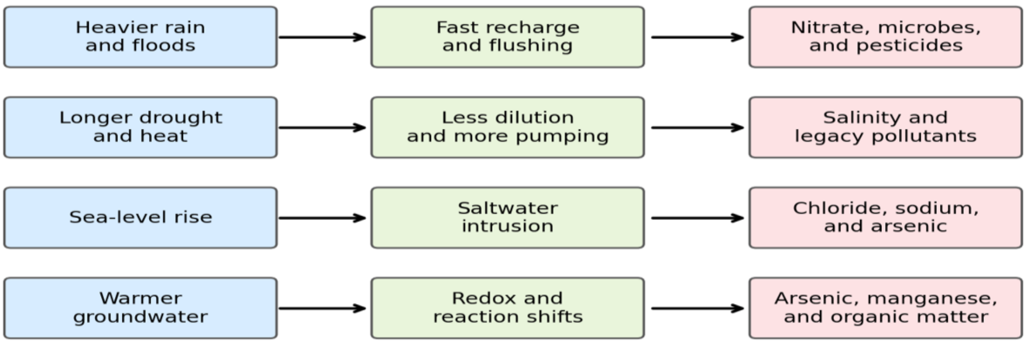

Figure 1 Weather signals can alter recharge, flow paths, and pollution behavior. Sources: IPCC (2022), UNESCO (2022), and Dow et al. (2024).

Evaluation Methodology and Evidence Base

This paper uses a systematic narrative review method. The assessment focuses on the consequences of climatic factors and groundwater contamination. It uses refereed articles, general definitions, and open data sources. Prefers studies with clear methods and measurable outcomes.

The evidence base includes global reports and regional case studies. Gravitational studies include satellites, field chemistry, microbial sampling, national hazard mapping, and machine learning. This combination is important. Groundwater pollution is not just controlled by the climate. It is also controlled by groundwater type, well depth, land use, pumping, and drainage.

The paper uses general data values where direct analysis is possible. The analysis compares water losses based on GRACE across three regions. Summarize the nitrate findings of a large study in the United States. He also paints a multi-hazard exposure plant in Bangladesh. These figures are not just temporary items. These are actual visual summaries based on published general values.

Review handles uncertainty carefully. Climate impacts may vary by region. Heavy rains may reduce the recharge in some moist soils. This same rain can add high energy to broken or sandy water layers. Drought can reduce the leakage of pollutants into an environment, but it increases their quantity elsewhere. For this reason, the paper avoids a simple general answer.

Table 1 Key Sources of General Evidence.

Sources	Type of data or evidence	Uses in this paper
ICCC Working Group II AR6	Climate Impacts and Water Cycle Guides	Formation of Climate Risks of Water Systems
UNESCO World Water Development Report 2022	Groundwater and Climate Change Assessment	Explains shipping, dehydration, and salinity issues
NASA Grace & Grace-FAO	Satellite Water Storage Data	Supports reduction comparison
U.S. Geological Survey (NWIS) and Water Data APIs	Water Level and Water Quality Data	Shows recurring monitoring paths
EPA Climate Index	Climate Trends, Statistics and Data	Supports the context of heavy rains
World Bank Bangladesh Report	Groundwater Hazard Map and Exposure Limits	Supports a multi-risk case study
Nature Scientific Data Study in Chennai	Flood Chemistry and Microbial Data	Post Flood Pollution Support

Actionable Data Workflows for Redundancy

Publishable review is more robust when it involves business data workflows. This paper uses general values from published studies. It also describes how the researcher can repeat the same analysis through open data sets. The workflow is simple. It combines weather data, groundwater level data, and water quality data by space and time.

The first practical task is to compare storage stress. NASA Grace data can be downloaded each month as unusual groundwater storage objects. The researcher can select an area, calculate the trend, and compare it to years of drought and rising demand. It doesn't just prove pollution. Identifies places where quality risks may increase due to low storage and thinness.

The second practical function is the nitrate climate screen. The U.S. National Geological Survey can provide nitrate records for wells. General weather data can provide annual rainfall and temperature. The researcher can group the wells by province or substrate. The researcher can then test whether wet or warm years match the increase in nitrate. This simple design follows the logic of Leo et al. (2024).

The third practical task is to assess the safety of wells in the event of floods. After floods, samples can be taken from wells for electroconductivity, nitrates, chloride, total coliform and E. Collie could be found. The same wells should be re-sampled after recovery. The design comes after a study in Chennai. It helps to separate the short flood pulses from normal groundwater conditions.

The fourth practical task is to assess the salinity of the coast. The nearshore wells can be monitored in terms of conductivity, chloride, sodium, pH and water level. If the salinity increases after a lack of water or excessive pumping, the signal should be mapped. In arsenic-contaminated delta, dissolved oxygen and redox potential should also be measured. It helps to determine the dangers of salt and arsenic.

These tasks do not require expensive tools. Fundamental analysis can be done through spreadsheets, R, Python, or GIS. Clean sampling methods and quality testing are essential for field testing. All samples should include the date of the well, depth, type of well, date of flooding, and distance from sources of pollution. Without these details, the results can be difficult to interpret.

A strong thesis should also remember the boundaries. General data sets can be uneven. Some wells have multiple records, while others have a single sample. Some records are missing information about depth or land use. The accuracy of some weather data is almost accurate. These boundaries should be clearly defined. It doesn't make the work useless, but it does show the gravity of the allegations.

Table 2: Reproducible Public Data Workflows for Climate and Groundwater Pollution Research.

Practical work	General information required	Simple Analysis	Expected Production
Comparison of Storage Stress	NASA Expertise, Drought Logs, Pumping Reports	Trend of Loss of Water Storage	Drain Stress Map or Chart
Nitrate Climate Screen	USGS NWIS, Rain, Temperature	Annual nitrate and climatic compatibility	Direction of Nitrate of Provinces or Underground
Floodwell Survey	Pre and Post Flood Samples	Compare microbes and ions before and after a flood	Short Range Pollution Signal
Coastal Salt Test	Chloride, conductivity, water level, pumping	Monitoring of salt indices over time	Warning of Saline Water Leakage
Arsenic Chemistry Test	Arsenic, pH, DO, ORP, Conductivity	Test Links with Oxidation, Acidity and Salinity	Dangers of climate-sensitive arsenic

Climate pathways that alter groundwater pollution

Climate change impacts groundwater through several integrated pathways. The first way is to change shipping. Groundwater re-energizes from rainfall, snowmelt, rivers, canals, and marshy areas. Climate change can change every source. It can change the charging time, quantity, and speed (UNESCO, 2022; Lamma et al., 2018).

Heavy rains can increase the risk of pollution. The rapid movement of water can carry nitrates, bacteria, pesticides, and dissolved solids downwards. It occurs mostly in sandy soils, fractured rocks, karst and poorly sealed wells. It can also happen when flooding covers wells and sewerage systems. This can result in sudden shallow water pollution (Lamma & Krair, 2018).

Drought creates a different pathway of pollution. Reducing recharging reduces thinness. Low levels of groundwater can be concentrated in salts and nitrates. Prolonged dehydration also increases pumping. Pumping can change the directions of natural flow. This contaminant can draw shallow water towards deep supply wells. It can also mix water through reservoirs (USGS, 2022; Lamma, 2024).

Sea level rise poses a major threat to coastal water bodies. Fresh groundwater usually pushes saline water towards the sea. Pumping and sea level rise can upset this balance. Salt water can go in. Chloride and sodium come first. There may be other reactions. In some deltas, changes in salinity can help remove arsenic from sediments (Frisbee et al., 2024; Lamma, 2023).

Global warming can also change the chemistry of groundwater. Rising temperatures can accelerate the reaction and bacterial activity. This can change the conditions of redox. It can increase emissions in sensitive sediments of arsenic, manganese, iron, and organic matter. These effects depend on the type of underground and the flow path (Dow et al., 2024; Lamma, 2020).

Table 3 Major meteorological pathways that can affect groundwater pollution.

Climate Signal	Groundwater response	Pollution Route	General Pollution
Heavy Rains and Floods	Faster Recharge and Rise in Ground Water Level	Surface pollution goes downward	| | Nitrates, Bacteria, Pesticides, Soluble Solids
Prolonged dryness and heat	Low Recharge and Low Dilution	Pollution becomes concentrated and pumping increases	Nitrate, Chloride, Arsenic, Selenium
Sea Level Rise	Brian's interface is moving inward	Saline Water Infiltration and Geochemical Changes	Chloride, Sodium, Arsenic
Hot Ground Water	Rapid reactions, oxidation and pressure changes	Minerals and organic matter become more active	Arsenic, Manganese, Iron
Maximum Blend	Flood after drought or storm wave	Stored contaminants wash away quickly	Mixed Chemical and Microscopic Contamination

Analyze practical general data and case guides

This section includes practical analysis using general values from published studies. The goal is to show how real data can support the review paper. The data is based on values declared by open or documented sources. A researcher can do the same with complete datasets from NASA, the U.S. Geological Survey, the Environmental Protection Agency, and journal repositories.

The first practical analysis compares the water losses caused by satellites. Grace measures changes in the Earth's gravity. These changes help in assessing the loss of water storage. Rodell et al. (2009) (Mohammad et al., 2015a) discovered about 109 km³ groundwater loss in northwestern India between 2002 and 2008 (Lamma & Sallam, 2018). Famiglietti et al. (2011) found about 30.9 km³ of water loss in California's Central Valley between 2003 and

2010. Voss et al. (2013) discovered a water loss of about 143.6 km³ in the Tigris-Euphrates and western Iran region between 2003 and 2009 (Lamma, 2021c).

These storage losses are not contamination values in themselves. However, these are important for quality. Drainage can reduce attenuation and increase pumping pressure. The pump can carry contaminated shallow water even deeper. It can also transport saline or geogenic water to the supply areas. This reduces pollution and increases pollution. (Lamma et al., 2019)

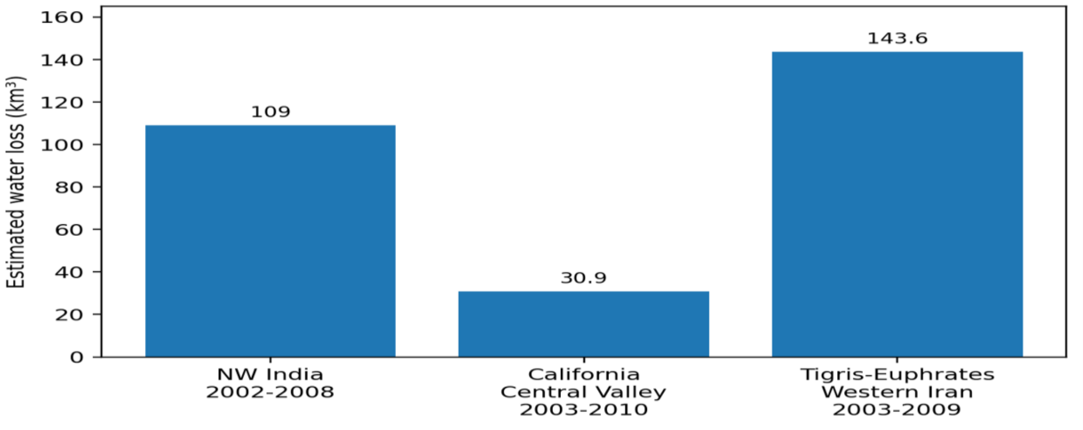

Figure 2: Groundwater loss and GRACE based water storage in the three stressed regions. Sources: Rodel et al. (2009), Famiglietti et al. (2011), Voss et al. (2013).

The second empirical analysis focuses on nitrates. Nitrates are a common contaminant of groundwater in agricultural areas. It is also sensitive to rain and temperature. Liu et al. (2024) (Lamma et al., 2019) used 293,775 nitrate notes throughout the continental United States. His model covered the period from 2001 to 2020. They found that rainfall and temperature testify to annual nitrate change in 75.2% of counties. They also found that 27 counties exceeded the nitrate limit at least once. (Zhmool et al., 2026a)

This result shows why climate data is important in groundwater quality studies. Anti-nitrate cannot be based on fertilizer alone. Rainy seasons, drought and recharge patterns are also important. A rainy year can push down stored nitrogen. Drought years can reduce thinning. Both conditions can pose risks in different places. (Zhmool et al., 2026b)

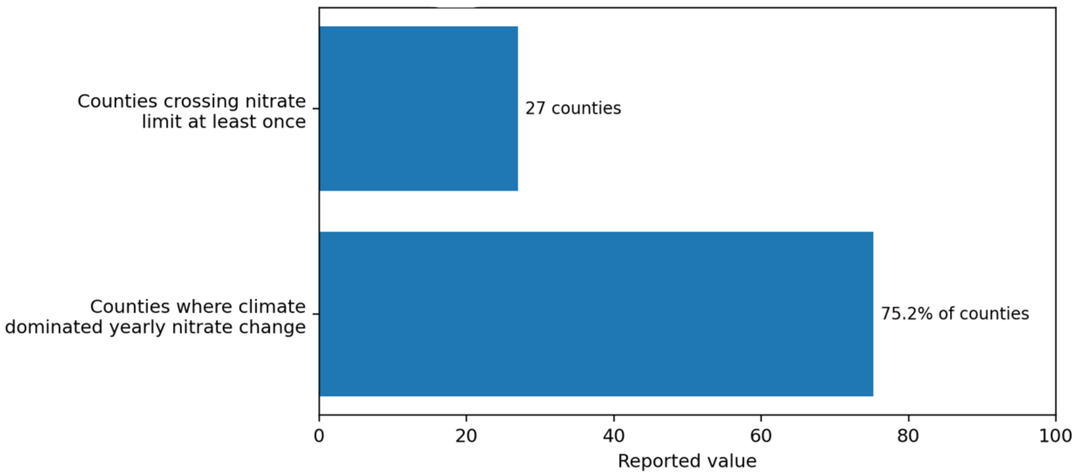

Figure 3: Nitrate indexes reported from a continental study in the United States [Liu et al. (2024)].

Bangladesh is a strong example of the overlap of groundwater hazards. The country is facing a shortage of arsenic, flood salinity, and groundwater. Shams Doha et al. (2019) (Mohammed et al., 2026) (Alshebgo et al., 2026) mapped the risks of multihazard groundwater in drinking water. The study found that 5% to 24% of the land experienced maximum co-risk. It is also estimated that between 6.5 million and 24.4 million people have been affected. The vulnerable poor population ranged from 2.2 million to 8.6 million.

This case shows that groundwater contamination is also a societal threat. Poor households can use shallow wells and poor health. They may also have fewer treatment options. Therefore, climate change can exacerbate health inequalities in groundwater pathways. (Alfarjani et al., 2026)

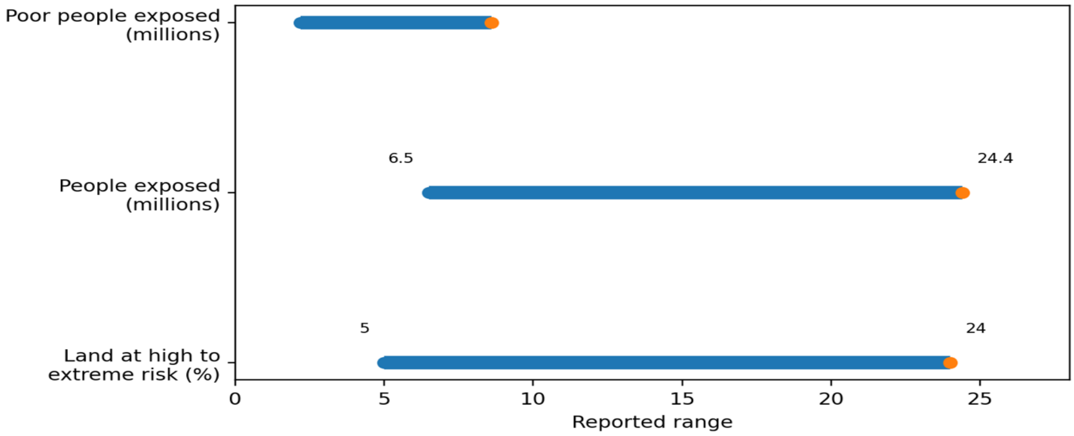

Figure 4 limits of multihazard high risk groundwater hazards in Bangladesh. Source: Shams Doha et al. (2019) and the World Bank.

Infiltration of coastal groundwater and salinity

Coastal water bodies are highly affected by the effects of climate change. Rising sea level increases pressure from the sea. Drying and pumping reduces pressure from the wildside. Both of these forces can move salt water inwards. The result is higher chloride, sodium, electrical conductivity, and total soluble solids.

It is difficult to stop the entry of salt water. Once the salt water enters the aquifer, it can take several years to wash it off. In some cases, the substrate is not restored during pumping. Coastal adaptation should be implemented quickly. Freshwater heads should protect and reduce pumping near the saltwater interface.

The chemical problem can be broader than chloride. Frisby et al. (2024) found that seasonal sea level rise and flooding may increase arsenic emissions in Bangladesh's well water. The study linked arsenic emission to less dissolved oxygen, less specific redox potential, and more specific conductivity. This means that salts can also cause geochemical hazards.

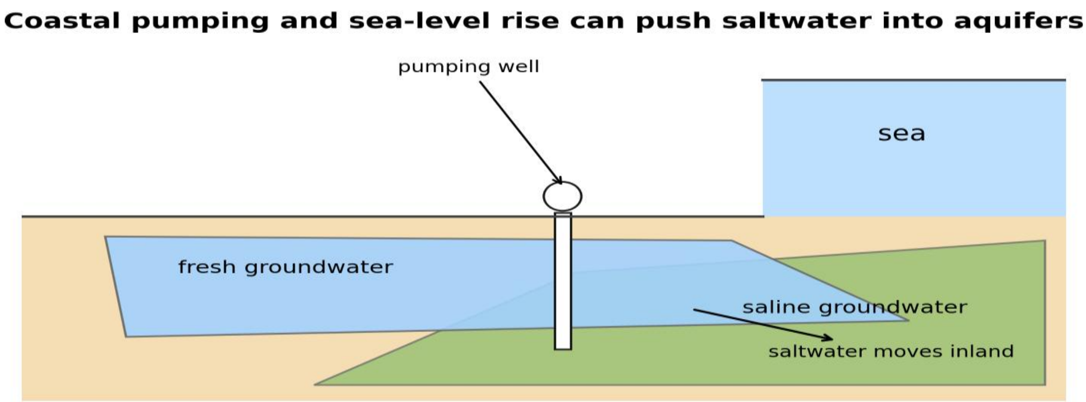

Figure 5: Conceptual portion of seawater intervention under coastal pumping and sea level rise.

Arsenic, Redox Conversion and Natural Pollutants

Not all groundwater pollution comes from the ground level. Some pollution is natural. Arsenic, manganese, iron, selenium, and radium can be obtained from groundwater reservoirs. Climate change continues to affect them. It can alter water levels, redox status, salinity, and flow paths.

Arsenic is a strong example of this. In many reservoirs of the delta, arsenic is preserved in sediments under certain chemical conditions. Flooding can reduce oxygen in groundwater. Organic matter can further reduce germs. Changes in salinity and pH can change the way arsenic adheres to metal surfaces. These changes can discharge arsenic into well water (Frisbee et al., 2024).

Deep wells are often used to avoid surface arsenic. This can be helpful when there is deep groundwater protection. It can fail when mud layers, pumps or geological windows connect shallow and shallow flow paths. Mihailov et al. (2020) showed that soil layers may explain the rise of arsenic in some of the reservoirs of Bangladesh. This finding warns against simple solutions.

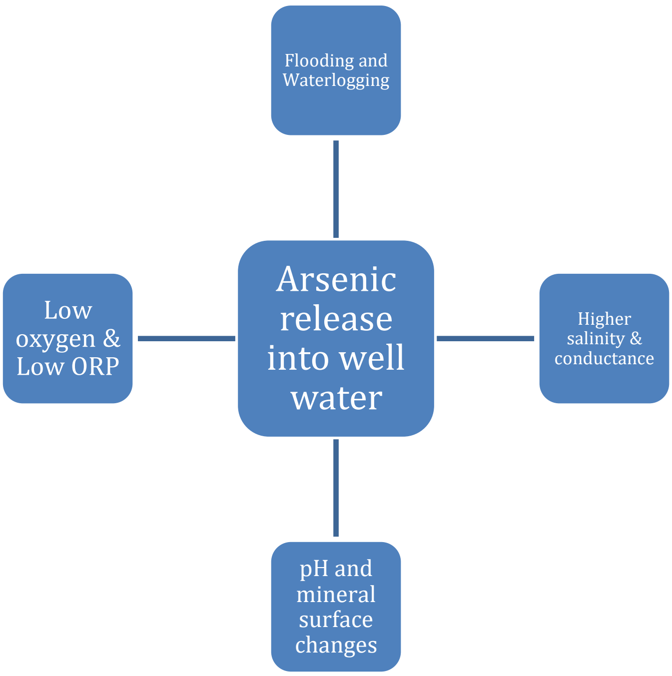

Figure 6: Key mechanisms by which climate-related changes can be released by water and arsenic chemistry. Sources: Frisbee et al. (2024) and Mihailov et al. (2020).

Floods, Bacteria and Shallow Wells

Flooding can cause rapid and direct pollution. It can cover wells, sewerage tanks, drains and waste sites. Contaminated flood water can enter wells through broken lid or weak seal. It can also enter shallow waters through rapid infiltration. This makes microbial hazards a major problem with regard to climate change.

Chennai flood study provides useful field evidence. Gaurisankar et al. (2017) took groundwater and surface water samples after the 2015 floods. The study said that the river water, which was contaminated with sewage, entered the wells. Large concentrations of bacteria and chemical ions were also found in many of the flood-affected areas. Some bacteria have also shown resistance to antibiotics.

Broken rocky reservoirs may weaken after heavy rains. Shapiro and Falconi (2022) mapped areas where high leakage could carry pollution with less reduction. This is important because pollution waves can bypass slow sampling programs. Surveillance should be more after floods and cyclones.

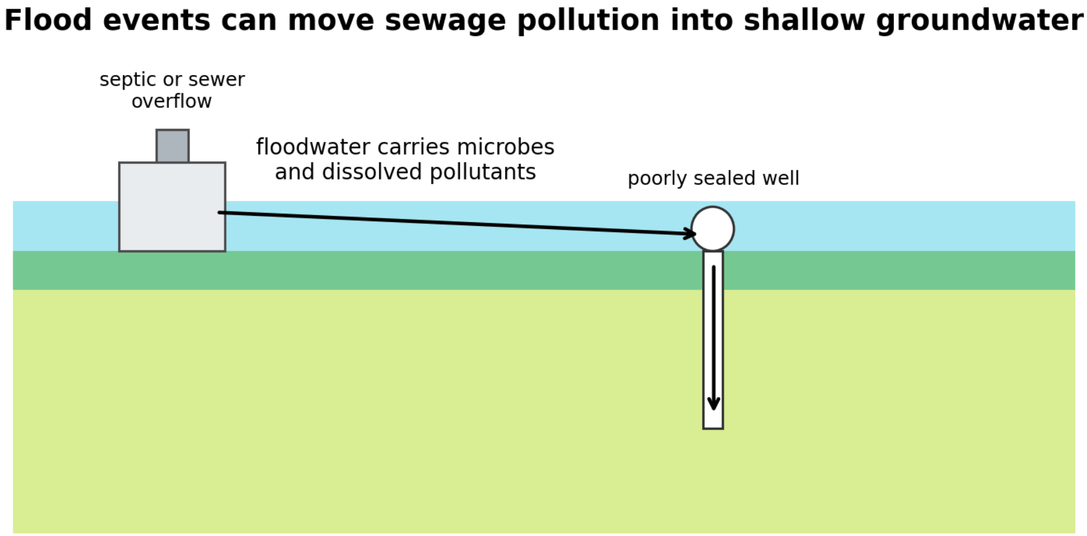

Figure 7 Flood path due to sewage flow into shallow groundwater and closure of faulty wells. Sources: Gorisenker et al. (2017) and Shapiro and Falconi (2022).

Results of the study

Large studies show a clear pattern. Climate change affects groundwater pollution through quantity, runoff, and chemistry. A single underground can face many hazards at once. Coastal reservoirs can withstand pumping due to saltwater infiltration, arsenic emissions, and drought. The shallow urban water body can withstand flooding, sewage and nitrate.

Table 3 compiles the most useful numerical results. These values support the data given in this paper. It also shows where more work can be done on public data. Future studies can upload entire data sets and replicate these analyses locally.

Table 4 : Selected Results of General and Controlled Groundwater Studies.

Area of Study	Data or Method	Reported Findings	Important Meanings
North West India	Gravity of the Grace satellite	Loss of about 109 km³ groundwater between 2002 and 2008	Deficiency can increase quality risk
Central California Valley	Gravity of the Grace satellite	About 30.9 cubic km of water wastaged from 2003 to 2010	Dehydration and Pumping Pressure
Tigris-Euphrates - Western Iran	Gravity of the Grace satellite	Total Water Loss from 2003 to 2009 approx. 143.6 km³	Loss of regional storage may affect salinity hazard
Continental United States	293,775 nitrate notes	Climate change dominates nitrate conversion in 75.2% of counties	It is important to calculate temperature and precipitation
Continental United States	The same nitrate study	27 provinces have exceeded nitrate limits at least once	Hotspots may change over time
Bangladesh	Multi-risk national mapping	5% to 24% of the Earth is more communally endangered	Arsenic, salinity, and decay interference
Bangladesh	Drawing of the same intensity	6.5 to 24.4 million people affected	The threat of groundwater is also a social threat
Chennai, India	Post Flood Field Sampling	Flood water and sewage entered the wells	Designing flood-proof wells is key

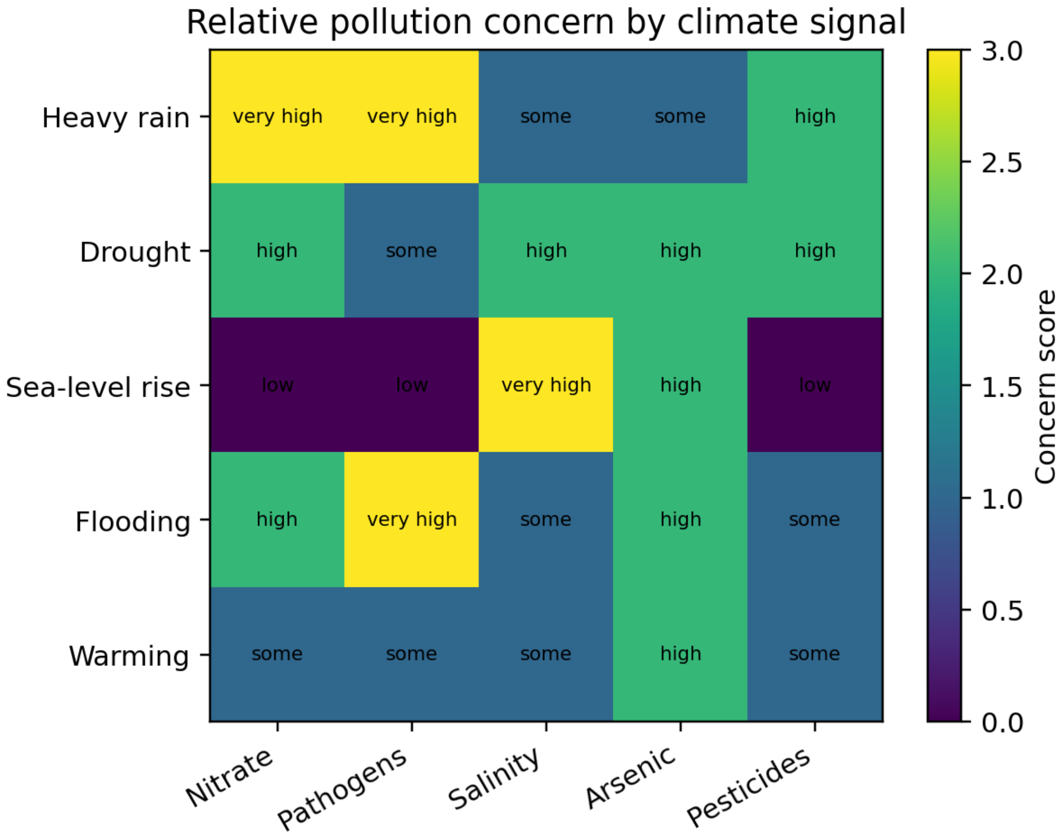

Figure 8 Artificial heat map showing relative concern regarding climate signal pollution. The grade is based on the studies reviewed in this paper.

Adaptation Strategies

Adaptation must begin with observation. Groundwater contamination is often caught late. Dense observation wells can feel the changes quickly. Monitoring should include water level, salinity, nitrates, arsenic, manganese, microbial indications, and well construction details. It should also record rainfall, flood events, droughts and pumping.

Open data systems are important. The USGS NWIS and USGS Water Data APIs show a useful model. Public water data allows students, agencies, and communities to examine trends. Open systems also make groundwater management more transparent. Supports early warnings after hurricanes and droughts.

Source control is still the cheapest protection. Climate change can rapidly shift nitrates and sanitation. She doesn't make it herself. Improved fertilizer time, reduction in excess nitrogen, safe dung storage, and improved cleaning reduce the burden. These measures should be more robust in recharge areas and flood-prone habitations.

Coastal areas need pumping control. Pumping near the Bryan interface should be limited. Wells should be kept away from infiltration routes. Monitoring should include chloride and conductivity. It should also include pH and oxidation indices in the arsenic-contaminated delta.

Charging regulated groundwater can be helpful, but it should be used with caution. It can store water during the rainy season for the dry season. It can also protect groundwater heads. However, poor groundwater can be contaminated. Recharge projects require pre-treatment, source water testing, anti-blockage, and long-term monitoring (Zhang et al., 2020).

Flood-protected water systems are absolutely essential. Wells should have elevated platforms, sanitary cells, and safe covers. Sewerage tanks should be moved or closed in flood-prone areas. Post-flood testing should be done before the wells can be reused. Emergency supplies should be ready for communities with less deep wells.

Treatment is the last hurdle. The World Health Organization points out that conventional treatments do not eliminate nitrates well. It can reverse osmosis, ion exchange, electrowashing, and remove biological detergents. Arsenic and salt treatment may also be required. However, the treatment is expensive. Prevention is still the best long-term strategy (WHO, 2022).

Figure 9 Adaptation Portfolio to Climate Sensitive Groundwater Pollution. Sources: WHO (2022), UNESCO (2022), USGS (2022), Zhang et al. (2020).

Table 5: Practical Adaptation Package for Climate Sensitive Groundwater Contamination.

Air Conditioning Procedures	Solution to the problem of pollution	Major Power	Important Warnings:
Intensive surveillance and open data	Late identification of nitrates, salts, minerals and bacteria	Discovers trends and trends in events	Continuous funding is needed
Closure of Wellhead and Raised Platforms	Microscopic organisms and wastewater intake from floods	Immediate Local Benefit	Often overlooked in a relaxed environment
Reduction in fertilizer time and load	Nitrate Leakage	Prevents contamination from the source	Benefits may be delayed
Coastal Pumping Control	Access to Saline Water	Protects the head of fresh water	Laws can be difficult to enforce
Management of Ground Water Recharge with Pre-Treatment	Water Scarcity and Storage Pressure	Stores water for dry seasons	The quality of feedwater should be safe
Sewer upgrades near recharge areas	Bacteria and Nitrates	Protects shallow subsurfaces	It takes planning and money
Targeted Drinking Water Treatment	Nitrates, Arsenic, and Salts	Provides quick protection to consumers	It can be expensive
Integrated Ground Water Governance	Divided decisions	Links between Weather, Quality and Health	The agency's cooperation is needed

Research and Policy Challenges

Many challenges remain. The first challenge is data coverage. There are a few observation wells in many reservoirs. Many wells are sampled only once or twice a year. This brief pollution may be ignored after the floods. More event-based sampling is needed.

The second challenge is old pollution. Nitrates and pesticides can live in soil and unsaturated areas. This source can reach groundwater several years after control is initiated. These delays can make policies look weak, even if they are slow.

The third challenge is size. Climate models work on a large scale. Wells respond at local scales. A village well can rely on a small area for charging. The city's well can draw water for several kilometers. There is a need for better local models.

The fourth challenge is governance. The quantity and quality of groundwater is often managed by different offices. Climate adaptation can be managed by another office. This separation slows down the work. A robust system that will integrate data on climate, groundwater, land use, sanitation, and public health.

The fifth challenge is justice. Poor households can use shallow wells that are unsafe. They can also live in areas where there is a risk of flooding. They may lack money for treatment. Adaptation plans must first protect at-risk users.

Conclusion

Climate change is affecting groundwater pollution in many ways. It alters food, dilution, pumping, salinity, redox conditions and flood paths. These changes can move or exclude pollution. It can also infect more people with unsafe drinking water.

The evidence does not support a simple global response. Each reservoir has its own season, geology, land use, and its own history of pumping. Heavy rains can push nitrates aside. Dehydration can concentrate nitrates in another category. Sea level rise could bring salinity and arsenic risks to the coastal delta.

Public data already supports robust research. NASA helps GRACE reveal the loss of storage. USGS systems provide water level and geological quality data. EPA indices show weather trends. Open journal datasets show flooding and arsenic processes. These resources can support student research and policy analysis.

The best way to adapt is prevention and integration. This will reduce pollution from the source. It will protect wells and recharge areas. This should be monitored promptly and regularly. Managed water recharge should be used only with quality assurance. It will treat drinking water where there is pre-exposure to it.

The recovery of groundwater after pollution comes slowly. This necessitates early action. Climate-resilient groundwater conservation is no longer just a water management issue but a public health requirement.

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