SOIL-WATER QUALITY MANAGEMENT

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The soil-water system acts as a substratum composed of organic matter, minerals, water, air, and microorganisms, which features ecosystem health. Soil, acting as a natural filter, ensures water quality, which includes its physical, chemical, biological and microbiological characteristics. Deforestation, unsustainable land use practices and climate change contribute to soil erosion, undermined soil quality, and altered precipitation patterns, affecting the balance of the soil-water system, and leading to more frequent droughts and floods. Moreover, various point sources and non-point sources of pollution have put the soil-water system at risk, eventually leading to groundwater contamination. Various kinds of pollutants, such as arsenic, fluoride, selenium, uranium, iron and petroleum hydrocarbons (non-aqueous phase liquid) have been found to contaminate soil-water systems. This article discusses a systematic a systematic undertaking, starting with a preliminary site assessment, examining historical records and inspecting the area for visible signs of contamination that is crucial to identify and manage a polluted site. The article provides insights on expertise approach for the polluted landscape management, which highlights local and climatic solutions.

Keywords: Soil, Groundwater, Contamination, Risk, Remediation, Management

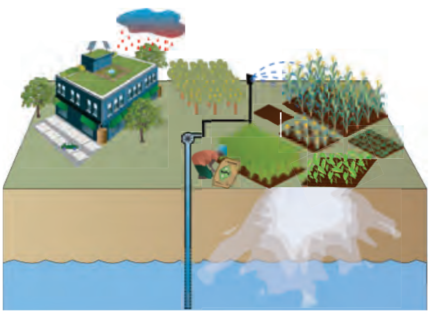
Understanding Soil-Water Quality

Soil is a living system of a complex mixture of organic matter, minerals, water, air, and microorganisms, and water being the universal solvent, is essential for the survival of all living organisms. Dynamic interaction between soil and water, including the movement, storage and availability of water within the soil, creates a system that can be delineated as a soil-water system (Gobat et al., 2004). Soil acts as a natural filter, purifying water as it percolates through the different soil layers it ultimately reaches the groundwater table. Soil quality refers to the ability of soil to perform its functions effectively and sustainably (Lal, 2019), which encompasses various physical, chemical and biological properties that influence the soil's ability to perform ecological services i.e., benefits people obtain from ecosystems, including provisioning (for example, food, water), regulating (climate, disease), supporting (nutrient cycling), and cultural (aesthetic, recreation) services (Suding, 2011). Whereas, water quality refers to the physical, chemical, biological and microbiological characteristics of water (Karr and Dudley, 1981), which determine its suitability for specific uses and its impact on the environment and human health. Soil-water systems are crucial for sustaining ecosystems and providing clean water. They play a vital role in agriculture, portable water supply and flood regulation, while also contributing to nutrient cycling and carbon sequestration, supporting both human well-being and environmental health (Visser et. al., 2019). But in recent decades, health and functionality of the soil-water system has become more susceptible to several threats.

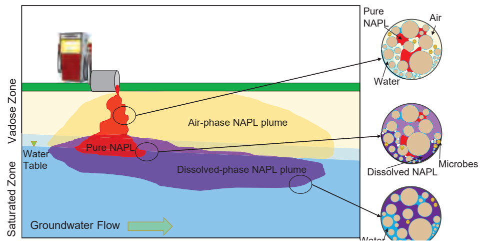
Pollution from agricultural return or runoff, industrial discharges, and improper waste disposal introduce harmful contaminants into the soil, leading to groundwater contamination and reduced water quality (Gupta, 2020). Over-extraction of groundwater for agriculture, industry, and urbanization without adequate recharge can deplete aquifers, causing a depletion in the water table and adversely impacting ecosystems and water availability (Dubey et al., 2022). Deforestation, unsustainable land use practices, and climate change contribute to soil erosion, undermined soil quality, and altered precipitation patterns, affecting the balance of the soil-water system, and leading to more frequent droughts and floods (Mainville et. al., 2006; Eekhout et. al., 2022). Urban development and impervious surfaces disrupt natural infiltration, causing increased stormwater runoff carrying pollutants into the water (Joshi and Gupta, 2018). It can also contribute pollution into the groundwater system, which originates from precipitation, snowmelt or surface water bodies and infiltrate into the soil through the unsaturated zone, also known as the vadose zone (Gupta and Sharma, 2019; Surinaidu et al. 2023). Eventually, groundwater contamination has now emerged as one of the major global challenges caused by various sources (Figure 1), ranging from human activities to natural processes. Some common sources of groundwater contamination include industrial activities, agricultural practices, landfills and waste sites, septic systems, fuel and oil spills, stormwater runoff, mining activities, geogenic sources, saltwater intrusion, and microbial contamination (Gupta, 2020).

Groundwater pollution can be categorized into point-source and nonpoint-source pollution based on the origin and the way contaminants enter the groundwater system (Kourakos et. al., 2012). Point-source pollution refers to contamination that originates from identifiable and discrete sources. These sources release pollutants at specific locations, making them easier to locate, monitor, and control. Some common examples of point-source pollution of groundwater include industrial outfalls, underground storage tank leaks (Gupta and Yadav, 2020), landfills and waste sites, septic systems and chemical spills, etc. Non-point source pollution refers to the contamination that comes from diffuse and widespread sources. These sources are harder to pinpoint because the pollutants enter the groundwater from multiple, dispersed origins. Examples of non-point source pollution of groundwater include agricultural runoff, urban runoff, atmospheric deposition, natural sources, saltwater intrusion, etc. Various kinds of pollutants such as arsenic, fluoride, Selenium, Uranium, Iron, and Petroleum Hydrocarbons (Non-aqueous phase liquid) have been found to contaminate soil-water systems (Gupta, 2020). For example, Rania-Khan Chandpur (Kanpur Dehat, UP); Lohiya Nagar (Ghaziabad, UP); Ranipet (A.P) and other places in India are famous for the Chromium contaminations in the soil-water systems (Prakash et. al., 2011; Vijay Kumar et. al., 2023). Chromium from the (COPR) Chromium Ore Processing Residue dump leakage, is a specific environmental issue related to the improper disposal and containment of waste from chromium ore processing (Matern et. al., 2017). As per MoEF&CC, contaminated sites are delineated areas in which the constituents and characteristics of the toxic and hazardous substances, caused by humans, exist at levels and in conditions that pose existing or imminent threats to human health and/or the environment. There are 240 major contaminated sites in India affected by industrial and geogenic pollutants (CPCB, 2023).

(a)



(b)



(c)

Fig. 1. Schematic diagram representing (a) point sources of contaminations; (b) non-point sources of contaminations; (c) leakage of petrochemicals (NAPL: Non-Aqueous Phase Liquid) from an underground storage tank in the subsurface environment.

Ways to manage such polluted sites

A systematic endeavour beginning with a preliminary site assessment, examining historical records, and inspecting the area for visible signs of contamination is indispensable to identify and manage a polluted site (Figure 2). A detailed site investigation follows, sampling and analysing soil, water, and air for pollutants (Ashraf et al. 2014; Saha et al. 2017). Risk assessments examine the potential hazards to human health and a suite of ecosystem services (Kuppusamy et al. 2017). The severity of contamination plays a crucial role; sites with larger areas or higher concentrations of pollutants may be prioritized. Additionally, the site's proximity to vulnerable populations and its ecological significance should be considered (Gupta and Bharagava, 2021). Moreover, sites with active or potential pathways of exposure should be given priority to prevent the further spread of contamination (Gupta and Yadav, 2020). To examine the state of contamination, performing a hydrogeological investigation at a contaminated site is a prerequisite which involves a systematic approach to understand the groundwater flow and the behaviour of contaminants (Gupta, 2020). This step is important to estimate the static properties (structure, depth, porosity, permeability—the ability of a fluid to flow through connected pores) and aquifer strength (good or low permeability), and dynamic properties (Relative permeability, capillary pressure, initial saturations, etc) of the soil-water system (Pepper et al., 2011). The process includes site characterization, installation of monitoring wells, groundwater sampling and analysis, hydraulic testing, and groundwater modelling. Site characterization helps to identify geological features and aquifers, while monitoring wells provide groundwater samples for contaminant analysis. Hydraulic testing determines aquifer properties, aiding in understanding groundwater flow patterns. Groundwater modelling simulates contaminant transport, predicting contamination extent and potential risks (Almaliki et. al., 2022; Guleria et al. 2023a).

To capture the behaviour of pollutants, characterizing the fate and transport of pollutants in the groundwater system involves a series of multiscale laboratory experiments and field tests to determine parameters like sorption, degradation rates, and dispersion coefficients, etc (Gupta and Yadav 2020; Gupta et al. 2023). Sorption is a crucial mechanism, whereby pollutants can adhere to soil particles, reducing their mobility and potentially leading to long-term retention in the subsurface. Additionally, biodegradation by microorganisms can break down some contaminants (Fouad et. al., 2023; Gupta and Gandhi, 2023), mitigating their impact over time. The flow of groundwater, governed by hydraulic conductivity and porosity, plays a significant role in transporting pollutants through the aquifer (Gupta and Yadav, 2020; Sarma and Singh, 2021). Dispersion and diffusion processes cause the spreading and dilution of contaminants within the groundwater flow, affecting their overall movement (Guleria et al., 2023b). The process typically includes conducting laboratory tests and field studies to determine key parameters influencing pollutant mobility. Groundwater flow and contaminant transport modelling are essential tools to simulate and predict the movement of pollutants over time. By integrating data from various sources, scientists can identify potential contaminant pathways, assess the risk to receptors and design appropriate remediation strategies to effectively manage and mitigate groundwater pollution, safeguarding water resources and human health.

The appropriate remediation technologies include methods such as pump-and-treat (Zha et. al., 2019), in-situ chemical oxidation (Wei et. al., 2022), bioremediation (Janssen et. al., 2020), permeable reactive barriers (Budania and Dangayach, 2023) or monitored natural attenuation (Ding et. al., 2022). The chosen remediation approach should align with site-specific conditions, hydrogeological properties, and the type of pollutants present. For bioremediation, suitable indigenous microbial populations or engineered microorganisms are selected to enhance the biodegradation of contaminants. Factors such as groundwater flow rates, nutrient availability and environmental conditions are considered to optimize microbial activity. The design may involve the installation of injection wells or bioventing systems to deliver nutrients or oxygen to contaminated zones (Gupta et al., 2021). Monitoring wells are established to assess the progress of bioremediation, and regular sampling is performed to analyse

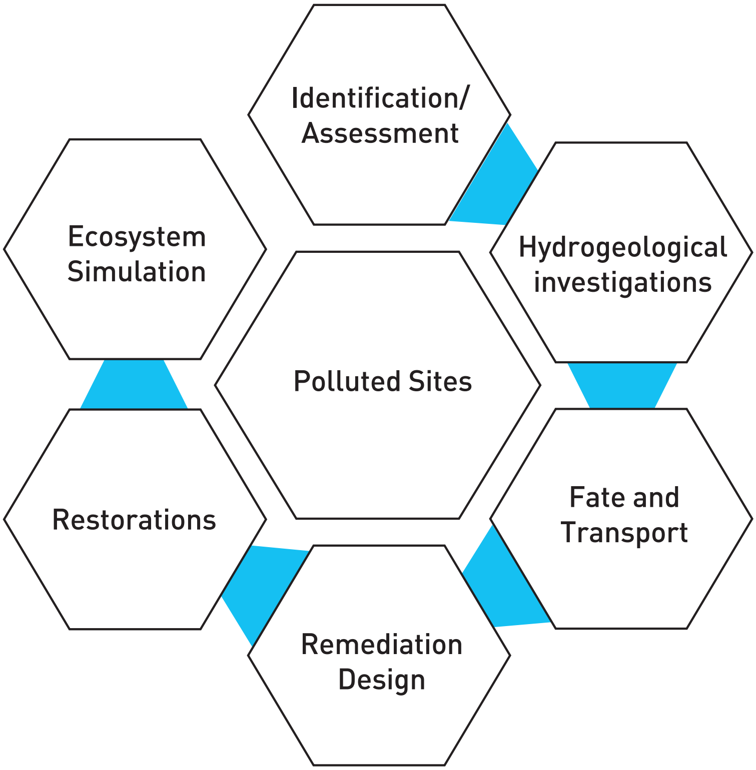


Fig.2: Flow of work plans or approaches for the remediation restoration and management of polluted sites.

pollutant concentrations and the effectiveness of the remediation process. Implementation involves the proper installation and operation of the selected remediation system, with regular monitoring to assess its effectiveness. Continuous adjustments and optimization may be necessary as the remediation progresses. Regular communication with stakeholders and compliance with regulatory requirements are critical throughout the remediation process.

During the post-implementation of any technological solution at a contaminated site, careful execution of the chosen methods is ensured, and progress is continuously monitored to assess effectiveness. Then, establishing a diverse planting scheme using a mix of native species to promote biodiversity and ecosystem health can anchor the success of restoration strategies. Monitor the growth and performance of the vegetation regularly and assess the plants' ability to uptake and sequester contaminants. Over the time, the selected native vegetation will aid in pollutant removal through phytoremediation and contribute to the site's rejuvenation, providing numerous ecological benefits and eventually transforming the polluted area into a thriving, self-sustaining habitat. Post-remediation, restoration efforts focus on reintroducing native vegetation, rehabilitating habitats, and ensuring the site's long-term health through regular monitoring and maintenance (Rivett et. al., 2002). Community engagement and education are integral to gain local support and participation in the restoration process. The ultimate goal is to achieve effective, sustainable and cost-efficient remediation that ensures the protection of soil-water quality and the environment while minimizing potential risks to human health.

Conclusion

Managing a polluted site requires a comprehensive and systematic approach to ensure effective remediation and environmental protection. Key messages for managing a polluted site include conducting a thorough site assessment to understand the extent of contamination and potential risks, adopting cost-effective integrated approach that combines appropriate remediation technologies and ensure compliance with environmental regulations and permits. Engagement with local communities and stakeholders throughout the process is crucial to address concerns and garner support. Regular monitoring and verification of remediation efforts, along with a focus on safety and health precautions for workers, contribute to successful site management. Emphasizing environmental sustainability, practicing adaptive management and maintaining transparent communication with all stakeholders are essential for achieving long-term restoration and safeguarding the health of the ecosystem and human populations. We must develop a restoration culture in India to manage polluted sites to produce safe drinking water for the world's largest population, which has safe drinking water as their fundamental right.

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