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Groundwater Contamination by Heavy Metals in Malaysia: Sources, Transport, and Remediation Strategies

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ABSTRACT: Groundwater contamination by heavy metals is a critical environmental issue, especially in areas dependent on groundwater. While Malaysia mostly relies on river water, certain states and islands rely heavily on groundwater. Limited research on heavy metal contamination in Malaysia's groundwater highlights the need for further study on pollutant distribution and mobility to develop effective remediation strategies. Human activities like landfills, mining, and fertilizer use contribute significantly to heavy metal pollution. Factors such as rainfall and low soil pH worsen leaching into aquifers. Techniques like 2D resistivity imaging and MODFLOW have helped assess contaminant transport, showing that concentrations decrease with depth and distance from pollution sources. Health risks from heavy metal exposure through groundwater consumption underscore the need for effective remediation. Phytoremediation is cost-effective for low concentrations, while permeable reactive barriers may suit more complex cases. This review evaluated current knowledge on contamination sources and distribution, as well as remediation methods, while identifying gaps in research on risk assessment and heavy metal speciation.

KEYWORDS: Groundwater contamination; heavy metals; remediation strategis; 2D phytoremediation; permeable reactive barrier

1. Introduction

The intensification of industrial and agricultural activities, coupled with the growing population, led to increasing water demand; hence, groundwater became a significant freshwater resource in most countries. Rapid urbanization and industrial development accelerated the degradation of the environment and the pollution of water resources on Earth, increasing the need for groundwater supply [1]. However, groundwater contamination became an alarming issue, especially in countries with high reliance on groundwater. In Malaysia, the main water supply was sourced from rivers, while groundwater contributed less than 10% of the total freshwater supply. The reliance on groundwater differed across states. In states such as Kelantan, Terengganu, Pahang, and parts of East Malaysia, groundwater was the primary freshwater source. On islands like Pulau Kapas, surrounded by seawater, groundwater served as the main freshwater source for drinking and daily activities, emphasizing the importance of addressing heavy metal contamination. Although groundwater use and reliance were currently low in Malaysia, the demand was expected to increase with continued development [2].

The main issue associated with heavy metals in groundwater was contamination. Apart from natural sources, the primary contributors to heavy metal pollution were anthropogenic activities such as landfills, mining, fertilizer usage, and industrial operations. The non-degradability of heavy metals allowed them to persist in aquifers, posing imminent threats to the environment, ecosystems, and human health [1]. Most studies on groundwater in Malaysia focused on its chemistry and seawater intrusion [2]. However, research on heavy metal contamination largely focused on soils and surface waters, such as rivers, rather than groundwater. Detailed analyses of heavy metals in groundwater were critical for understanding contaminant migration patterns and identifying appropriate remediation methods. This paper reviews the sources of heavy metals in groundwater, the studies on their distribution and transport, and current remediation methods for heavy metal contamination in groundwater.

2. Source, Distribution and Movement of Heavy Metal Contamination

Natural sources of heavy metals included the weathering and erosion of rocks and minerals, which released these metals into groundwater. Anthropogenic sources of heavy metals were classified as point sources and non-point sources (NPS) [3]. Landfills were one of the main point sources of heavy metal contamination. Most landfills in Malaysia were open dumpsites and non-sanitary, with only 18 sanitary landfills still operating. Non-sanitary landfills lacked essential facilities such as base liner systems and leachate treatment, increasing the risk of leachate contamination [4]. The percolation of leachate containing heavy metals from landfills into groundwater was a major issue. Heavy metals in leachate originated from the disposal of hazardous waste at the landfill site. Rainfall events increased leachate generation, promoting the mobilization of heavy metals from hazardous waste [5]. Leachate infiltration also polluted groundwater by disrupting soil environments and solubilizing heavy metals in the soil [6]. Without proper monitoring and management, continuous leachate generation after landfill closure could lead to groundwater contamination (Figure 1).

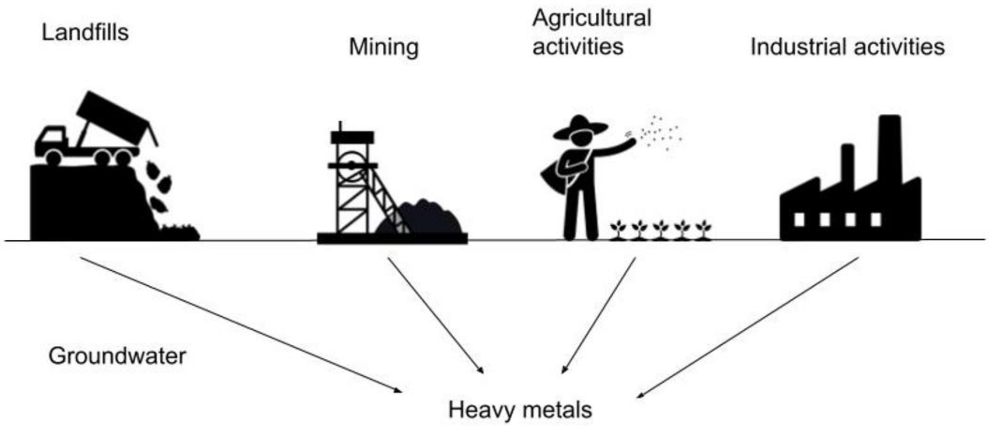

Figure 1. Source of heavy metals in the groundwater.

Mining sites were another point source of groundwater contamination. Heavy metal contamination occurred during both the operation and closure of mining sites. Acid mine drainage (AMD), produced by the weathering and oxidation of sulfide-bearing rocks, continued even after mining site decommissioning. AMD was acidic and contained high concentrations of heavy metals. AMD also originated from mining waste containing acid-generating minerals. The acidic conditions caused by AMD accelerated heavy metal leaching from rocks and soils. The disposal and spillage of mine tailings also contributed to heavy metal pollution [7]. The removal of protective soils during excavation further enhanced the migration of heavy metals from the soil into groundwater [3].

In agriculture, fertilizers and animal manure were applied to supply essential nutrients for plant and crop growth. However, fertilizers and manure containing heavy metals were identified as non-point sources of groundwater contamination [3]. Soluble heavy metals reached groundwater through irrigation water percolating through the soil. Groundwater was contaminated by surface runoff and heavy metal leaching from the ground into groundwater, exacerbated by rainwater infiltration. Overuse of fertilizers could induce acidic soil conditions, promoting the release of heavy metals and facilitating their migration into groundwater [8].

Advection described the transport of contaminants along with groundwater flow, where the contaminant moved at the same velocity as groundwater. Dispersion referred to the spread of the contamination plume over a large area due to variations in porosity and hydraulic conductivity. Contaminant transport retardation included sorption processes, which played a significant role in the natural attenuation of heavy metals in soil, reducing their concentration in groundwater. Groundwater flow and distribution significantly affected the migration and distribution of heavy metal contaminants [9,10]. Rainwater infiltration was a key factor in the leaching of heavy metals into groundwater, mobilizing metals from soils and surface layers. Fluctuations in the groundwater table, especially in shallow regions, promoted the release of heavy metals into groundwater, with acidic soil conditions further contributing to increased heavy metal concentrations [11,12]. As soil pH decreased, heavy metal solubility increased, and sorption decreased, resulting in the leaching of heavy metals into groundwater [13].

Yussoff et al. found that levels of Fe, Cd, Cu, Ni, and Pb exceeded safety limits in groundwater samples. The source of Fe contamination was traced to steel industry waste at the Ampar Tenang landfill. The study revealed a downward migration trend of the contamination plume, with increased concentrations of heavy metals like Cu, Mn, Pb, and Ni. The concentration of contaminants declined as the radial distance from the landfill increased. In terms of vertical distribution, heavy metal concentrations generally decreased with depth below 60 cm, except for Pb and Zn [13]. Samuding et al. studied groundwater and contaminant distribution at the Taiping landfill, generating contour plots that illustrated the localized southeast migration of heavy metals, including Cd, Cu, Pb, and Fe, along with groundwater flow [14]. In Chandigarh, Ravindra and Mor found the highest concentration of Fe in groundwater, likely sourced from Fe-bearing minerals and waste dumping sites. They also discovered high concentrations of Ni and Zn near dumping sites, with zinc contamination traced to dust and fertilizer use. Concentrations of Zn, Ni, Cd, and Pb exceeded safety limits [15]. At a non-sanitary landfill near the Kelang River, heavy metals such as Fe, Pb, Mn, and Ni migrated from surface soils into groundwater, with vertical distribution profiles showing increased concentrations in underlying soils [16].

2.1.Studies of the contaminants in groundwater and application of mathematical models.

The studies on the migration and movement of contaminants existing in the groundwater are significant to prevent the occurrence of enhanced groundwater contamination which causes hazardous impact to human health and environment through consumption of contaminated groundwater. Table 1 includes numerous studies on the application of 2D resistivity imaging and MODFLOW in delineating contamination plume, assessing the groundwater flow and contaminant transport.

Table 1. Application of 2D resistivity imaging and MODFLOW in groundwater system.

Model and technique	Groundwater study	Location	References
2D resistivity imaging, RES2DINV inversion software	Contamination plume	Landfill nearby Kelang River	[16]
2D resistivity imaging, RES2DINV inversion software	Contamination plume	Taiping landfill	[14]
2D resistivity imaging, RES2DINV inversion software	Contamination plume	Taiping landfill	[17]
2D resistivity imaging, RES2DINV inversion software	Contamination plume	Sungai Sedu landfill	[18]
2D resistivity imaging, RES2DINV inversion software	Contamination plume	Seri Petaling landfill	[19]
MODFLOW	Flow	Taman Beringin landfill	[22]
MODFLOW	Flow and contaminant transport	Ampar Tenang landfill	[13]
MODFLOW	Flow and contaminant transport	Kham Bon landfill	[23]
MODFLOW MT3DMS	Flow and contaminant transport	Xiangtan mining area of Mn	[24]
MODFLOW	Contaminant transport	Cattle farm at ladang 16	[25]

2.1.1. 2D resistivity imaging.

Two pairs of steel electrodes are used for transmission of direct current (DC) to the ground and measurement of electrical potential respectively. The interpretation of resistivity data after measurement allows identification of subsurface features including the contamination plume, soils and rocks which have electrical conductivity. After measurement of the subsurface resistivity, the interpretation of resistivity data is completed using RES2DINV inversion software. The soluble ions in the leachate including inorganic contaminants and heavy metals induce the electrical conductivity of the samples hence causing the low resistivity value of leachate [14, 18].

The study conducted by Rahim Bahaa Eldin et al. delineated the contamination of groundwater and subsoils by landfill leachate. The site investigated is a non-sanitary landfill located nearby Kelang River and the results of the study illustrate the migration of leachate from the landfill to the Kelang River. The decline in the value of electrical resistivity indicates higher concentration of leachate in the soils and groundwater. Low resistivity value of the contamination plume which is less than 10 Ohms shows the position of contamination while the leachate plume migration to Kelang River in the northwest direction is also illustrated in the resistivity profile [16]. The low resistivity value of 10 Ohms is also shown in the study by Samsuding et al. at Taiping landfill [14]. The high porosity of the soils and the abundance of kaolinite contribute to the easy migration of leachate to the groundwater below at the landfill site [16].

In another study conducted by Samsudin et al., the delineation of contamination plume in groundwater can be achieved using geoelectric resistivity imaging technique. In the case of Taiping landfill, the large zone of low resistivity value as illustrated in 2D resistivity image indicates the migration of leachate towards soil and groundwater, even exceeding the landfill site boundary. There is a downward movement of leachate plume as low resistivity anomaly is observed [17]. Hamzah et al. investigate and analyses the migration of leachate at Sungai Sedu

Landfill. The clayey soils found on the landfill site which are characterized by low porosity inhibits the leachate migration in both vertical and horizontal direction, according to the results of resistivity modeling [18]. Using the same technique, it is discovered that the flow direction of leachate and the groundwater flow is the same at Seri Petaling landfill in the study conducted by Mukhtar et al [19].

2.1.2. MODFLOW.

The governing equation using finite difference method in simulating the saturated groundwater flow is associated with Darcy's Law and the equation of 3D groundwater flow is shown below:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t}$$

The transport and movement of the contaminants in groundwater involving the transport mechanism such as dispersion and advection is simulated using MT3DMS model:

$$\frac{\partial(wC^k)}{\partial t}=\frac{\partial}{\partial x_i}\left(wD_{ij}\frac{\partial C^k}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(wv_iC^k)+q_sC_s^k+\sum R_n$$

Using the numerical model requires assignment of the boundary condition as the groundwater flow can be influenced by other water bodies or groundwater sinks and sources. The calibration of the model is conducted through modification of the data inputted. The limitations of the model are the average or estimated input data will cause imprecise simulation results of the groundwater flow and contaminant movements in groundwater [20,21]. The study conducted by Atta, Yaacob and Jaafar used MODFLOW modeling on the steady-state flow of groundwater to assess the groundwater flow and the possible pollutants transport at the Taman Beringin ex-landfill. Some of the assumptions made in the modeling include steady-state flow, isotropic and uniform hydraulic conductivity. Based on the modeling results, the movement of groundwater flow to the southeast and northeast direction of the landfill site which are Nanyang and Wahyu ponds and Jinjang River respectively is observed. The hydraulic connection between these water bodies and the aquifer below the landfill site can cause the transport of pollutants to the water bodies along with the flow of groundwater. To induce the recharging of the groundwater by the river and prevent pollution of the water bodies, hence pumping to achieve groundwater table reduction below the river bed is recommended [22].

Yusoff et al. assess and investigate the migration of pollutants sourced from the leachate generated at Ampar Tenang Landfill. According to the results of MODFLOW modeling and other analysis of groundwater characteristics, the downgradient movement of heavy metals including Pb, Fe, Cu, Cd and Mn is concluded, indicating that the contaminant transports along with the local groundwater flow [13]. The simulation of heavy metals transport which are Cr, Cd and Pb in groundwater at the landfill site in Thailand is conducted by Tantemsapya et al. The occurrence of heavy metals migration from the ground surface to the groundwater is within the 500m radius of landfill and lead has the highest degree of migration followed by chromium, as indicated by the simulation result of 20 years period. Apart from that, the direction of groundwater flow towards east is shown through the results [23].

The transport of manganese sourced from manganese ore area in China is simulated under a period of 20 years using the same model by Xie et al. Based on the results of the study, the movement of manganese to the groundwater from the point source which is the manganese ore is observed with increased time and the pollutant migration coincides with the groundwater flow. The speed of plume diffusion will decrease as the covered range of diffusion increases however this relationship changes in vertical plume migration as the migration speed increases upon reaching of layer 3. The maximum distance of diffusion range is around 2291 metres at the end of simulation period [24]. Another study conducted by Ebrahim et al. involves simulation of contaminants sourced from the cattle farms to determine the contaminants concentration and contaminant transport using Visual MODFLOW software. From the simulation results of one year period, there is reduction in the concentration of targeted contaminants including copper, nitrate and potassium through time, where the concentration of copper is less than 0.0557 mg/l [25].

3. Potential Health Impact and Environmental Impact of Heavy Metals in Groundwater

Surface water contamination can occur when polluted groundwater interacts with connected water bodies, threatening aquatic organisms through exposure to heavy metals. The reduction in aquatic species leads to the degradation of ecosystems and disrupts food chain relationships. The persistence of heavy metals in groundwater can cause bioaccumulation in aquatic organisms and agricultural crops, which then affects human health when consumed (Figure 2). Heavy metals found in crops come from their absorption through roots and wastewater irrigation [26]. Human exposure to heavy metals via groundwater and food consumption poses serious health risks. Lead, for example, can damage the nervous system and kidneys, with children particularly vulnerable to neurological impairment [27, 30]. Lead exposure is also linked to neurological diseases like Parkinson's and Alzheimer's. Nickel exposure can cause lung fibrosis and skin allergies [29], while mercury can result in kidney damage and respiratory failure. Arsenic exposure damages the circulatory system and increases cancer risk. Chromium and cadmium lead to renal and liver damage, while excessive manganese intake damages the nervous and respiratory systems [27, 30]. Table 2 highlights the health impacts and sources of different heavy metals.

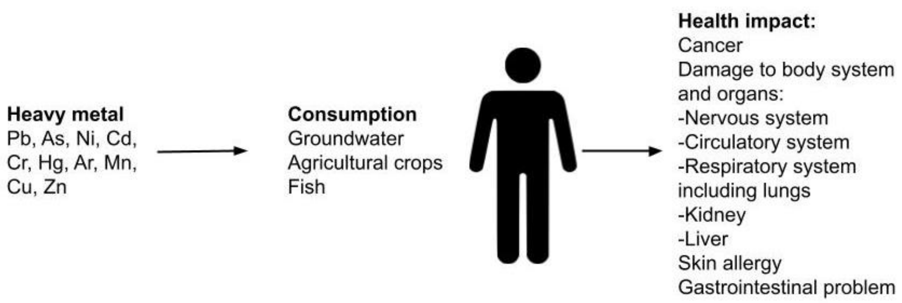

Figure 2. Health impact of heavy metals.

In Malaysia, anthropogenic sources of groundwater heavy metal contamination include landfills, mining, and agriculture. The delineation of leachate plumes at Malaysian landfills is done using 2D resistivity imaging to detect contaminant migration in groundwater. Mathematical models like MODFLOW are used to simulate groundwater flow and contaminant transport. These analyses help map groundwater systems and contamination distribution, enabling the selection of effective remediation methods to mitigate groundwater pollution. Future research on heavy metal risk assessments in groundwater can analyze the potential environmental and health risks posed by contamination. The characterization of soil properties and heavy metal speciation is essential for understanding their bioavailability and how this affects leaching from soils into groundwater [32, 33]. Studies on implementing remediation technologies at contaminated groundwater sites in Malaysia should be prioritized to protect groundwater resources and minimize hazardous impacts on the environment.

Table 2. Sources and health impacts of heavy metals in groundwater.

Heavy metals	Sources	Health impact	Reference
Pb	Fossil fuel combustion, battery manufacturing, pigments, solders, paint manufacturing, Caulking, cable covers, mining, plumbing, gasoline	Damage to nervous system and brain, Parkinson's disease, Alzheimer's disease damage to liver and kidney, cardiovascular disease, impairment of brain on children, lead poisoning, muscle weakness, anorexia, hypertension	[27–30]
Ni	Fossil fuel combustion, electroplating, nickel alloy, steel and metal plating industries, gasoline, diesel, mining, stainless steel manufacturing,	Cancer, asthma, lung fibrosis, hypersensitivity, skin allergy,	[27–30]
Hg	Fossil fuel combustion, mining,	Renal damage, lung fibrosis, damage to nervous system, abdominal and chest pain, Young's syndrome, diarrhea	[27, 28, 30]
Ar	Fossil fuel combustion, manufacturing of cement, chemicals and glassware, pulp and paper production, mining, iron ore smelting,	Cancer, damage to circulatory system and neurological system, cardiovascular disease, Gastrointestinal problem, Guillain-Barre disease, hypertension	[27– 29, 31]
Cr	stainless steel welding , pigment manufacturing, electroplating, tannery industry	Damage to nervous system, allergic dermatitis, liver and lung damage, respiratory tract cancer, gastrointestinal problem, necrosis, diarrhea, damage to kidney.	[27–30]
Cd	PVC stabilizers, electronic compounds, Battery manufacturing, zinc and lead refining, vessels coating, plastic industries, pesticides, pigments	Damage to nervous system, kidney and liver, necrosis, hypertension, diarrhea, deformed bones.	[27, 28, 30]
Mn	Steel alloys and iron	Brain disorder, Parkinson's disease, cardiovascular disease, hypertension, respiratory problems	[28, 30]
Zn	Steel industries, mining, coal combustion, smelting, fertilizers	Prostate cancer, gastrointestinal problems, muscle cramp, anemia, cardiac problems, diarrhea, damage to kidney, abdominal pain,	[27, 28, 30]
Cu	smelting and refining, Fossil fuels combustion, piping, mining,	Liver and kidney damage, gastrointestinal problems, Wilson's disease, diarrhea	[28, 30]

4. Remediation Method of Heavy Metal Contamination.

The objectives of heavy metal remediation include stabilizing contaminants to reduce toxicity and mobility, significantly degrading them, separating and recycling unpolluted substances from contaminated ones, extracting and treating or disposing of contaminants, and containing them to prevent further environmental exposure. Remediation methods for heavy metal contamination in groundwater fall into three categories: biological treatment, physico-chemical treatment, and chemical treatment [34]. Table 3 outlines various remediation methods, along with their advantages and disadvantages.

Biological treatments, such as phytoremediation and biosorption, are cost-effective. Biosorption involves using biosorbents like plants, agricultural waste, fungi, and bacteria, which bond with heavy metals [35]. Biosorption is highly efficient and reduces sludge production, but its application is currently limited to laboratory-scale studies, and further field testing is needed for groundwater treatment [34]. Soil washing is suitable for sites with severe contamination, but its drawback lies in the hazardous extraction agents or chelating agents used, which can alter soil environments and create toxic effluents. Chelate flushing faces challenges due to the non-biodegradability and high cost of chelates [34].

Electrokinetic remediation uses direct current to cause electromigration and electro-osmosis, moving metal ions toward the electrodes. The effectiveness of this method depends on factors such as soil porosity, pH, ion mobility, and pollutant concentrations [34, 36]. It is more efficient in low-permeability soils like clay and kaolinite than in high-permeability soils [34]. However, when heavy metal concentrations are lower than the soil's sorption capacity, higher energy consumption is required, increasing costs [37].

Table 3. Remediation methods of heavy metal contamination in groundwater.

Remediation methods	Mechanism	Heavy metals	Pros and cons	Reference
Phytoremediation	Uptake of heavy metals through roots	Pb, Cr, Cd, Ni, Zn, Cu	Pros: -Low cost Cons: -Long treatment period -Slow plant growth rate	[34, 35]
Permeable reactive barrier	Zero valent iron: chemical reduction of the contaminants Activated carbon: removal of contaminants through absorption Lime: neutralization of groundwater and removal of heavy metals through precipitation	Pb, Zn, Sb, Co, Mn, As, Cu, Cr, Ni, Cd, Mo, Hg	Pros: -Low operation and maintenance cost -Little interference to the ground Cons: -Replacement of reactive media -Requires detailed site investigation -Restricted treatment for contaminant movement towards the barrier	[34, 41, 44]
Electrokinetic remediation	Application of direct current in soils moves ions to the electrodes	Pb, Zn, Cr, Cd, Ni, As, Mn, Hg, Co	Pros: -Easy operation High efficiency Cons: -Have many side effects -Factors including the soil characteristics, heavy metal concentrations and ionic mobility affect the treatment	[34, 36, 37]
Biosorption	Binding of heavy metals with the biosorbent	Pb, As, Zn, Cd, Ni, Fe, Cr, Cu	Pros: -Low cost -Biosorbent regeneration -reduction in sludge production -High efficiency	[34, 35]
Soil washing	Washing and extraction of contaminants using chelating agents and organic solvents	Pb, As, Zn, Cr, Mn, Cu, Cd, Fe, Mo, Co, Hg, Ni, Al	Pros: -High efficiency -Reduction in soil volume which is contaminated Cons: -High cost of extracting agents -Disturbance and changing properties of soil -Disposal of hazardous soil	[34, 45]

4.1. Pyhtoremediation.

The mechanisms of phytoremediation for inorganic contaminants, including heavy metals, are as follows. In phytostabilization, groundwater pollutants are absorbed by plants and accumulated in their roots and tissues, immobilizing the contaminants and preventing their further movement. In phytoextraction or phytoaccumulation, pollutants are absorbed into the upper parts of plants. After the phytoextraction process is complete, bioenergy and recoverable metals can be extracted by burning the plants. Phytovolatilization involves the transformation and volatilization of absorbed contaminants, such as selenium, arsenic, and mercury, into the atmosphere, reducing their toxicity. Plants used in phytostabilization can also prevent water percolation into soil layers, though contaminants remain immobilized in the soil [38, 39]. Groundwater remediation often involves rhizofiltration, where contaminants are precipitated or absorbed in the rhizosphere. Ideal plants for rhizofiltration have extensive root systems and strong heavy metal accumulation abilities, such as for copper, chromium, and lead. Terrestrial plants are preferred over aquatic plants due to their more developed root systems [39, 40].

Metal hyperaccumulators are plants used in phytoremediation that can absorb high concentrations of heavy metals without harm to themselves. Phytoremediation is cost-effective and efficient for removing heavy metals from groundwater, especially in low concentrations and large areas. Additionally, bioenergy production from the plants used in phytoremediation is feasible if they produce high biomass and accumulate significant amounts of heavy metals. However, phytoremediation is time-consuming and unsuitable for urgent remediation needs. Other limitations include the plant’s maximum accumulation capacity and root contact with groundwater heavy metals. The disposal of plants containing accumulated heavy metals must be managed carefully to avoid environmental hazards [38].

4.2.Permeable reactive barrier.

A permeable reactive barrier (PRB) is an in-situ remediation method for treating contaminated groundwater. The barrier contains reactive media that groundwater passes through, allowing treatment as contaminants interact with the media. The higher permeability of the PRB compared to the surrounding aquifer facilitates the movement of groundwater through the barrier, enhancing remediation. The reactive media must not contribute to further contamination, should be cost-effective, and should be durable to minimize replacement costs. Additionally, the particle size of the media should be moderate to avoid hindering the natural groundwater flow [41].

PRB remediation relies on three mechanisms: degradation, precipitation, and sorption. In chemical degradation, contaminants are reduced by zero-valent iron (ZVI) as they pass through the barrier. ZVI oxidizes during the process and is especially effective in treating metals with high oxidation states [41, 42]. Sorption involves the absorption of contaminants using media like zeolites and granular activated carbon, without altering the contaminants' chemical state. Activated carbon is highly effective at absorbing heavy metals. In precipitation, pollutants are immobilized without changing their chemical form. For instance, limestone is commonly used to treat acid mine drainage (AMD), as it neutralizes acidic groundwater and decreases metal solubility. However, the use of alkaline materials can lead to barrier clogging due to metal precipitation, reducing treatment efficiency [41, 43].

PRBs offer several advantages, including their effectiveness in treating a wide range of pollutants, not just heavy metals. They have low operation and maintenance costs, and since treatment occurs underground, there is minimal disruption to surface activities. However, the reactive media in the PRB must be replaced periodically. The successful application of PRBs requires thorough investigation of site hydrogeology, geology, and the hydraulic performance of selected media. Another limitation is that PRBs are not effective for contamination plumes deeper than 20 meters. Moreover, treatment is limited to areas where contaminants flow towards the barrier, making it crucial to first delineate the contamination plume [41, 44].

5. Conclusion

Groundwater is increasingly becoming a vital freshwater resource amid Malaysia's rapid development. However, the presence of heavy metals in groundwater poses a growing concern due to the risk of contamination. It is crucial to identify anthropogenic sources of heavy metals and understand the migration pathways of these pollutants into groundwater. Studies on contaminant transport along groundwater flow provide valuable insights into the presence of heavy metals, with tools like geoelectrical resistivity imaging and MODFLOW assisting in groundwater system simulations. Mapping contaminated groundwater is essential for effectively implementing remediation methods to address groundwater pollution. Further, more comprehensive studies are needed to assess groundwater risks, including the bioavailability of heavy metals. Understanding the potential health and environmental impacts of heavy metal contamination is key to mitigating its effects. Current remediation methods such as phytoremediation, permeable reactive barriers, electrokinetic remediation, and soil washing each have their own advantages and limitations. A detailed investigation of site-specific characteristics, including geology and hydrogeology, is crucial for optimizing the performance of the chosen remediation techniques. The feasibility and practical implementation of these methods in Malaysia require further study to ensure the protection of groundwater resources.

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Author Contribution

Wei Lin Wong: : Writing, Conceptualization, Data Collection; Mehmet Emre: Writing, Methodology; Gaurav Talukdar: Methodology, Review.

Competing Interest

The authors declare that there are no competing interests or conflicts of interest regarding the publication of this review article.

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