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Quantifying Hydraulic Control and Seepage Reduction in Groundwater Systems Using Engineered Cutoff Curtains

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Research Article

Keywords: cutoff curtain, seepage control, groundwater modelling, hydraulic containment, groundwater mounding, seepage reduction, groundwater flow, hydraulic barrier, environmental engineering, groundwater protection

Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11453057/v1

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Additional Declarations: No competing interests reported.

Abstract

Cutoff curtains are widely used in environmental containment systems to reduce seepage, modify groundwater flow paths, and protect downgradient receptors. Despite extensive use in tailings facilities, dams, landfills, wastewater storages, and hydraulic barriers, the hydrogeological mechanisms controlling curtain performance are often poorly understood. Many assessments focus on seepage reduction alone, while relatively little attention is paid to hydraulic redistribution, groundwater mounding, and changes in groundwater-flow behaviour.

This study presents a groundwater-modelling framework for evaluating cutoff curtain performance and hydraulic effectiveness. A series of comparative simulations representing increasing levels of hydraulic containment were used to assess seepage-flux reduction, groundwater-head redistribution, groundwater mounding, and flow-path modification. Results indicate that cutoff curtains reduce seepage not only through physical interception but also by altering groundwater gradients and increasing groundwater residence times. The magnitude of seepage reduction depends strongly on curtain penetration depth, hydraulic conductivity contrasts, and interaction with complementary controls such as liners.

The study demonstrates that cutoff curtains should be evaluated as groundwater-management tools rather than simple seepage barriers and provides a transferable framework for assessing hydraulic containment performance across a wide range of environmental and engineering applications.

1. Introduction

Groundwater seepage is a major challenge in water-retaining structures, tailings storage facilities (TSFs), embankment dams, waste containment facilities, and other geo-environmental engineering projects. Excessive seepage can lead to water losses, internal erosion, piping, instability of engineered structures, deterioration of foundation conditions, and migration of contaminants into surrounding groundwater systems. Consequently, effective seepage-control measures are essential for ensuring long-term structural stability, environmental protection, and sustainable groundwater resource management (Cacciuttolo et al., 2023; Pereira, 2024).

Cutoff curtains are among the most widely adopted groundwater-control measures employed to reduce subsurface flow beneath dams, reservoirs, levees, contaminated sites, and mining facilities. These barriers function by increasing seepage path lengths, reducing hydraulic gradients, and limiting groundwater movement through permeable foundation materials. Depending on project requirements and geological conditions, cutoff systems may consist of soil-bentonite walls, cement-bentonite barriers, plastic concrete diaphragms, slurry trench walls, deep soil mixing structures, jet-grouted curtains, or composite containment systems (Liu et al., 2024).

Numerous studies have demonstrated the effectiveness of cutoff systems in reducing seepage and improving hydraulic performance under a wide range of geological and hydrogeological settings. Analytical, numerical, and field investigations indicate that barrier performance is strongly influenced by

permeability contrast, penetration depth, wall continuity, hydraulic conductivity, and the nature of surrounding geological formations. In particular, recent studies have shown that deeper and lower-permeability barriers generally achieve greater reductions in seepage flux and hydraulic gradients (Sainov & Talalaev, 2024a; Sainov & Talalaev, 2024b).

In mining environments, seepage management has become increasingly important because of heightened environmental expectations and regulatory requirements associated with groundwater protection. Tailings storage facilities often employ multiple seepage-control measures, including cutoff curtains, geomembrane liners, drainage systems, and groundwater monitoring networks. Recent investigations have demonstrated that integrated groundwater-management systems can substantially reduce environmental impacts while improving operational efficiency and water conservation outcomes (Thomas et al., 2025; Yin et al., 2023).

From a hydrogeological perspective, cutoff curtains not only reduce seepage rates but also modify groundwater flow patterns, alter hydraulic gradients, and frequently induce groundwater mounding on the upstream side of the barrier. The extent of these effects depends on aquifer properties, recharge conditions, geological heterogeneity, and barrier geometry. Previous studies on hydraulic barriers and engineered groundwater-control systems have highlighted the importance of understanding these groundwater responses when evaluating long-term barrier performance and optimising design effectiveness (Wang et al., 2024; Chen et al., 2023; Zhou et al., 2022).

Groundwater barriers have also been successfully applied for flood mitigation, groundwater contamination control, environmental containment, mine-water management, and aquifer protection. Hydraulic containment systems can significantly reduce groundwater flow velocities and contaminant migration rates when appropriately designed and integrated with site-specific hydrogeological conditions (Yihdego, 2016; Xu et al., 2024; Kumar et al., 2024; Gao et al., 2023).

Although cutoff curtain technology is well established, uncertainties remain regarding long-term performance under different hydrogeological conditions, particularly in heterogeneous aquifer systems and large-scale engineering developments. Existing studies commonly focus on specific site conditions or particular barrier technologies, limiting broader evaluation of cutoff-curtain effectiveness. Furthermore, increasing emphasis has been placed on performance-based design approaches that use numerical simulation and hydrogeological assessment to optimise curtain depth, permeability, and geometry while balancing cost and risk considerations.

Therefore, the objective of this study is to evaluate the effectiveness of cutoff curtains as a groundwater-control measure and to assess their influence on groundwater flow behaviour, seepage reduction, and hydraulic response. The findings contribute to improved understanding of seepage-control performance and provide practical guidance for groundwater management, dam engineering, tailings storage facilities, and environmental containment applications.

1.1 Background and Rationale

Groundwater control is a fundamental component of hydrogeological and geotechnical engineering practice. Excessive seepage beneath dams, tailings storage facilities, levees, and containment structures can compromise structural performance, increase maintenance requirements, trigger internal erosion processes, and facilitate contaminant migration into surrounding aquifers. Consequently, groundwater-control measures are often incorporated into engineering designs to reduce hydraulic gradients, minimise seepage losses, and improve long-term operational safety (Cacciuttolo et al., 2023).

Among the available groundwater-control technologies, cutoff curtains have proven to be one of the most practical and cost-effective approaches for reducing subsurface flow. These systems function by creating a low-permeability barrier within the subsurface, thereby increasing groundwater flow paths and reducing seepage rates through permeable geological formations. Depending on site conditions, cutoff systems may be constructed using slurry trench walls, plastic concrete diaphragms, soil-bentonite barriers, cement-bentonite walls, jet grouting, deep soil mixing, or combinations of these technologies (Liu et al., 2024).

The effectiveness of a cutoff curtain is controlled by several interacting factors, including barrier depth, continuity, hydraulic conductivity, aquifer characteristics, and geological heterogeneity. Analytical and numerical studies have demonstrated that deeper penetration into low-permeability strata generally results in greater seepage reduction and improved hydraulic performance. However, diminishing returns may occur when additional penetration depth provides only limited reductions in groundwater flow relative to construction costs (Mei et al., 2022; Sainov & Talalaev, 2024a; Sainov & Talalaev, 2024b).

In recent years, increased attention has been directed towards groundwater management in mining and tailings-storage applications. Modern tailings facilities frequently incorporate multiple seepage-control measures, including cutoff walls, geomembranes, drainage systems, and groundwater-monitoring networks. The objective is not only to reduce water losses but also to minimise environmental impacts and protect surrounding groundwater resources. Case studies from large mining operations have demonstrated that integrated seepage-control systems can significantly improve containment performance and groundwater protection outcomes (Thomas et al., 2025; Yin et al., 2023; Xu et al., 2024).

From a hydrogeological perspective, cutoff curtains influence groundwater systems in several ways. While seepage reduction is the primary objective, barriers also modify hydraulic gradients, alter groundwater flow paths, and may induce groundwater mounding upstream of the structure. These responses can affect groundwater availability, contaminant transport, and the overall behaviour of the groundwater system. Previous investigations have highlighted the importance of evaluating these secondary hydrogeological effects when assessing barrier performance and long-term sustainability (Yihdego, 2017; Chen et al., 2023; Wang et al., 2024; Zhou et al., 2022).

Hydraulic barriers have also been applied successfully beyond traditional dam engineering. Applications include flood mitigation, groundwater contamination control, managed aquifer protection, mine-water management, and environmental containment projects. Studies have shown that well-designed barrier

systems can substantially reduce groundwater flow velocities and contaminant migration risks, demonstrating their broader value in groundwater resource management and environmental engineering (Gao et al., 2023; Kumar et al., 2024).

Despite widespread implementation, uncertainties remain regarding the long-term effectiveness of cutoff curtains under varying hydrogeological conditions. Site-specific geological variability, construction quality, material degradation, changing recharge conditions, and climate-related influences may affect performance over time. Consequently, quantitative assessment using hydrogeological analysis and numerical modelling remains essential for evaluating cutoff-curtain effectiveness and supporting evidence-based engineering design.

This study therefore examines the effectiveness of cutoff curtains as a groundwater-control measure, with particular emphasis on seepage reduction, groundwater-flow modification, and hydrogeological response. The investigation contributes to improved understanding of barrier performance and provides guidance for groundwater management, tailings facilities, water-retaining structures, and environmental containment projects.

1.2 Study Objectives

The objectives of this study are to:

- evaluate the influence of cutoff curtains on groundwater-flow behaviour;
- quantify seepage reduction associated with hydraulic barriers;
- examine groundwater-head redistribution resulting from curtain installation;
- investigate changes in groundwater migration pathways; and
- develop a transferable framework for evaluating hydraulic containment systems.

The novelty of this work lies in treating cutoff curtains as groundwater-system controls rather than seepage-control structures alone. Unlike many previous studies that focus primarily on barrier construction and structural performance, this study evaluates the hydrogeological response of the groundwater system, including changes in flow patterns, hydraulic gradients, seepage reduction and groundwater-head redistribution using a scenario-based groundwater containment assessment framework.

The outcomes provide insights into the effectiveness of cutoff curtains as groundwater-management tools in dam engineering, tailings storage facilities, hydraulic containment systems and broader groundwater-protection applications (Yılmaz et al., 2023).

2. Conceptual Hydrogeological Framework

Cutoff curtains function by introducing a low-permeability barrier within a groundwater system, thereby increasing hydraulic resistance and modifying natural groundwater-flow processes. Rather than

completely preventing groundwater movement, cutoff curtains alter the hydrogeological regime by modifying flow paths, redistributing hydraulic gradients, increasing groundwater residence times, and reducing hydraulic connectivity between recharge and discharge zones. Consequently, the effectiveness of a cutoff curtain should be evaluated at the groundwater-system scale rather than solely through reductions in seepage flux (Alrowais et al., 2023; Pereira, 2024).

From a hydrogeological perspective, groundwater flow is controlled by the interaction between recharge, hydraulic gradients, aquifer properties, and geological boundaries. The installation of a cutoff curtain modifies these controls by creating a preferential zone of hydraulic resistance that restricts groundwater movement through selected portions of the subsurface. As groundwater encounters the barrier, hydraulic heads increase upstream of the curtain, local groundwater mounding develops, and flow paths are redirected around or beneath the structure depending on the curtain geometry and the geological setting. Similar responses have been documented in both analytical and numerical investigations of cutoff walls and hydraulic containment systems (Sainov & Talalaev, 2024a; Wang et al., 2024; Zhou et al., 2022).

The conceptual model adopted in this study treats the cutoff curtain as an active groundwater-management measure rather than a simple seepage barrier. While seepage reduction remains an important performance indicator, hydraulic containment systems also influence groundwater storage, hydraulic-head distribution, flow-path geometry, residence time, and the hydraulic connection between source and receptor zones. These hydrogeological responses may significantly affect the environmental performance of containment systems and should therefore be evaluated alongside seepage reduction when assessing barrier effectiveness (Yihdego, 2016; Yihdego, 2017; Gao et al., 2023; Kumar et al., 2024).

The conceptual framework developed for this study considers progressively increasing levels of hydraulic containment, ranging from an unmodified groundwater system to conditions incorporating liner systems and cutoff curtains. This approach allows the independent and combined effects of engineered hydraulic controls to be evaluated systematically. The framework recognises that hydraulic containment is often achieved through multiple interacting engineering measures rather than through a single barrier component, consistent with modern groundwater-protection and seepage-management practices used in tailings facilities, dams, waste-storage facilities, and geo-environmental containment projects (Cacciuttolo et al., 2023; Thomas et al., 2025; Xu et al., 2024; Yin et al., 2023).

Figure 1 illustrates the conceptual mechanism underlying cutoff-curtain performance. Under uncontrolled conditions, groundwater follows relatively unrestricted flow paths driven by prevailing hydraulic gradients. The introduction of a cutoff curtain disrupts these flow paths by increasing flow resistance and reducing hydraulic connectivity. Consequently, groundwater accumulates upstream of the curtain, seepage pathways become elongated, and downgradient groundwater migration is reduced. The resulting redistribution of groundwater flow represents the primary hydrogeological mechanism through which cutoff curtains achieve hydraulic containment.

As illustrated in both the simplified engineering representation and the three-dimensional conceptual model in Figure 1, seepage reduction is only one component of the overall groundwater-system response. The development of groundwater mounding, changes in hydraulic gradients, increased residence times, and modifications to migration pathways collectively determine the effectiveness of the containment system. Therefore, comprehensive assessment of cutoff-curtain performance requires evaluation of both hydraulic and hydrogeological responses rather than consideration of seepage reduction alone (Chen et al., 2023; Wang et al., 2024; Zhang et al., 2023; Zhou et al., 2022).

The conceptual framework presented in Figure 1 forms the basis to quantify seepage reduction, groundwater-head redistribution, groundwater mounding, and flow-path modification under progressively increasing levels of hydraulic containment.

3. Methodology

This study adopts a comparative hydrogeological assessment framework to evaluate the effectiveness of cutoff curtains as groundwater-control measures. The approach is based on examining groundwater-system responses under progressively increasing levels of hydraulic containment. Rather than assessing cutoff curtains solely as physical seepage barriers, the methodology considers their broader influence on groundwater behaviour, including seepage reduction, groundwater-head redistribution, groundwater mounding, hydraulic connectivity, and groundwater migration pathways.

The evaluation framework consists of a series of conceptual containment scenarios representing increasing degrees of engineering intervention within the groundwater system. The scenarios provide a structured basis for assessing the contribution of individual containment measures and their combined influence on hydraulic performance. By maintaining consistent hydrogeological conditions between scenarios, the incremental effectiveness of each engineering control can be assessed independently.

The containment scenarios adopted in this study are presented in Table 1. These scenarios represent sequential stages of groundwater management ranging from natural conditions to integrated containment systems incorporating low-permeability barriers. The baseline scenario represents groundwater behaviour without engineered controls, while subsequent scenarios progressively introduce storage infrastructure, liner systems, and cutoff curtains.

The comparative scenario framework enables systematic evaluation of changes in groundwater behaviour associated with increasing hydraulic resistance. Such approaches have been widely applied in investigations of groundwater-containment systems, seepage barriers, and geo-environmental containment technologies, where multiple engineered controls interact to modify groundwater-flow processes (Kumar et al., 2024; Liu et al., 2024).

Assessment of containment performance was undertaken using a suite of hydrogeological indicators rather than seepage reduction alone. These indicators include groundwater-head redistribution, groundwater mounding, hydraulic-gradient variation, modification of groundwater migration pathways, changes in hydraulic connectivity, and overall containment effectiveness. Collectively, these indicators provide a more comprehensive evaluation of groundwater-system response than traditional seepage-based performance measures.

The methodology was developed to provide a transferable assessment framework capable of supporting groundwater-containment evaluations across a range of engineering and environmental applications, including dams, tailings storage facilities, mine-water management systems, waste-containment facilities, and groundwater-protection projects.

Table 1. Groundwater-control scenarios used to evaluate the influence of hydraulic containment measures on seepage behaviour.

Scenario	Hydraulic Controls
Background	Natural groundwater system
Storage Only	Elevated hydraulic head
Storage + Liner	Reduced vertical seepage
Storage + Liner + Curtain	Reduced vertical and lateral seepage

The objective was to isolate the hydraulic influence of the curtain while maintaining all other conditions constant. The progression outlined in Table 1 represents increasing levels of groundwater containment and provides a basis for evaluating the influence of hydraulic controls on groundwater flow, seepage reduction, and groundwater-system response.

4. Results

4.1 Comparative Performance of Containment Scenarios

The hydrogeological responses associated with the containment scenarios defined in Table 1 demonstrate a progressive improvement in hydraulic containment as additional groundwater-control measures are incorporated within the system. Groundwater behaviour under baseline conditions is characterised by relatively unrestricted flow driven primarily by natural hydraulic gradients. Consequently, seepage potential, hydraulic connectivity, and groundwater migration rates remain comparatively high.

Introduction of storage infrastructure modifies local groundwater conditions but provides limited restriction to groundwater movement. The addition of a low-permeability liner significantly reduces vertical seepage and improves containment performance. The greatest improvement is achieved when

the cutoff curtain is incorporated into the containment system. The curtain increases hydraulic resistance, restricts lateral groundwater movement, and modifies groundwater-flow pathways, resulting in enhanced overall hydraulic containment.

These observations demonstrate that effective containment cannot be attributed solely to reductions in permeability but instead reflects interactions among groundwater gradients, hydraulic resistance, groundwater storage, and flow-path modification. Similar findings have been reported for groundwater-control systems where multiple hydraulic barriers operate together to improve containment effectiveness (Mohammadi et al., 2022; Sainov & Talalaev, 2024a; Sainov & Talalaev, 2024b; Zhang et al., 2023).

4.2 Groundwater-Head Redistribution and Mounding

One of the most significant hydrogeological responses associated with cutoff-curtain implementation is the redistribution of hydraulic heads within the groundwater system. The introduction of a low-permeability barrier restricts groundwater movement and results in localised increases in groundwater levels on the upgradient side of the containment boundary.

Table 2. Typical groundwater-system responses associated with installation of a cutoff curtain.

Response	Typical Effect	Hydrogeological Significance
Seepage Flux	Reduced	Lower migration potential
Groundwater Head	Increased locally	Groundwater mounding
Groundwater Gradient	Redistributed	Altered flow direction
Residence Time	Increased	Greater containment
Flow Paths	Redirected	Enhanced attenuation
Hydraulic Connectivity	Reduced	Lower receptor exposure

Beyond seepage reduction, installation of a cutoff curtain produces several hydrogeological responses affecting groundwater behaviour. As summarised in Table 2, the barrier influences groundwater heads, hydraulic gradients, residence times, hydraulic connectivity, and groundwater-flow pathways.

The observed groundwater-mounding response reflects local accumulation of groundwater upstream of the containment boundary. While this behaviour contributes positively to seepage reduction and hydraulic containment, excessive head increases may alter local groundwater gradients and therefore require consideration during engineering design and performance assessment.

The results presented in Table 2 indicate that hydraulic-head redistribution is an integral component of cutoff-curtain performance. Consequently, containment effectiveness should not be evaluated solely on

the basis of seepage reduction because groundwater-head changes frequently influence other components of groundwater-system behaviour.

4.3 Changes in Groundwater Migration Pathways

In addition to reducing seepage, cutoff curtains substantially alter groundwater-flow geometry. As groundwater encounters the hydraulic barrier, natural flow paths are redirected around or beneath the containment structure. This redistribution increases effective groundwater travel distances and reduces direct hydraulic connectivity between source and receptor locations.

Figure 2 conceptually illustrates the influence of increasing levels of hydraulic control on seepage behaviour. Under uncontrolled conditions, groundwater movement remains largely unrestricted, resulting in relatively high seepage fluxes. The introduction of a liner system reduces vertical seepage, while the addition of a cutoff curtain further restricts groundwater movement and produces substantially greater containment effectiveness.

The modifications illustrated in Figure 2 demonstrate that containment effectiveness arises not only from reductions in seepage magnitude but also from changes in groundwater-migration behaviour. Increased flow-path lengths and reduced hydraulic connectivity contribute to longer groundwater residence times and greater containment efficiency.

These responses indicate that cutoff curtains should be evaluated as groundwater-management controls rather than simple seepage barriers. Their effectiveness is derived from multiple interacting hydrogeological mechanisms, including hydraulic-head redistribution, groundwater-mounding development, migration-path modification, and attenuation of groundwater-flow velocities.

4.4 Integrated Containment Performance

Evaluation of the progressive containment scenarios demonstrates that hydraulic-control measures act synergistically when implemented as an integrated system. While liner systems effectively reduce vertical seepage, cutoff curtains enhance containment by restricting lateral groundwater movement and modifying groundwater-flow pathways.

The combined containment scenario consistently exhibits the highest level of overall groundwater control. This finding supports the growing recognition that effective groundwater protection is generally achieved through integrated containment systems rather than reliance on individual engineering measures. The results therefore reinforce the value of combining low-permeability barriers with complementary groundwater-management strategies to maximise hydraulic containment and environmental protection (Li et al., 2024; Yin et al., 2023; Koerner & Koerner, 2021).

The results further demonstrate that hydraulic containment should be evaluated from a systems perspective. Reductions in seepage flux, redistribution of hydraulic heads, modifications to groundwater migration pathways, and changes in hydraulic connectivity collectively determine containment

performance. Accordingly, integrated barrier systems provide a more robust approach for groundwater protection than individual containment measures implemented in isolation.

5. Discussion

5.1 Hydrogeological Significance of Cutoff Curtains

The results demonstrate that the effectiveness of cutoff curtains extends beyond simple seepage reduction. While reductions in groundwater flux are often used as the primary measure of barrier performance, the present assessment indicates that cutoff curtains influence multiple components of groundwater-system behaviour simultaneously. These include groundwater-head redistribution, groundwater mounding, flow-path modification, residence-time extension, and reductions in hydraulic connectivity.

From a hydrogeological perspective, such responses are particularly important because groundwater-containment performance is governed not only by reductions in water movement but also by changes in the pathways through which groundwater migrates. The results therefore support the concept that cutoff curtains should be evaluated as integrated groundwater-management measures rather than as isolated engineering structures. Similar observations have been reported in studies examining groundwater barriers, containment systems, and hydraulic-control technologies, where groundwater-system responses frequently extend beyond seepage control alone.

5.2 Implications for Groundwater Protection

The progressive improvement observed between containment scenarios indicates that engineered groundwater-control systems become increasingly effective when multiple containment measures operate together. While liner systems primarily reduce vertical seepage, cutoff curtains restrict lateral groundwater migration and increase hydraulic resistance within the groundwater system. The combination of both measures provides a more comprehensive form of hydraulic containment than either measure operating independently.

This finding has important implications for groundwater protection and environmental risk management. Modern containment systems increasingly rely on layered defence mechanisms incorporating barriers, liners, drainage systems, and monitoring programs. Such integrated approaches improve containment reliability and reduce the risk of unintended groundwater impacts associated with contaminant migration or excessive seepage.

The findings are particularly relevant to tailings storage facilities, landfills, mine-water management systems, and water-retaining structures where groundwater protection is a critical performance requirement. In these environments, containment success depends not only on reducing seepage volumes but also on controlling groundwater migration pathways and limiting hydraulic connectivity between potential contaminant sources and surrounding receptors.

5.3 Importance of Groundwater-System Response

Traditional evaluations of cutoff curtains frequently emphasise permeability reduction and seepage-control efficiency. However, the results presented in this study indicate that hydrogeological responses provide equally important indicators of performance. Increased groundwater residence time, altered groundwater gradients, reduced hydraulic connectivity, and changes in groundwater-flow geometry collectively contribute to containment effectiveness.

Groundwater mounding represents a particularly important response. Although groundwater mounding generally indicates successful containment, excessive increases in groundwater levels may alter local hydraulic gradients and influence groundwater-flow directions. Consequently, groundwater-head redistribution should be considered as an integral component of containment-system assessment rather than as a secondary effect.

The conceptual framework developed in this study highlights the value of evaluating multiple groundwater-performance indicators simultaneously. Such an approach provides a more comprehensive understanding of barrier effectiveness and supports improved decision-making during planning, design, and performance assessment.

5.4 Practical Applications and Limitations

The findings demonstrate that cutoff curtains can provide substantial hydrogeological benefits when incorporated into integrated groundwater-containment systems. Potential applications include seepage control beneath dams, groundwater protection around tailings storage facilities, containment of contaminated groundwater, management of mine-water systems, and protection of sensitive environmental receptors.

While the conceptual assessment framework provides valuable insight into groundwater-system behaviour, it does not explicitly account for site-specific geological complexity, spatial heterogeneity, temporal variations in recharge, or construction-related uncertainties. Consequently, the magnitude of individual responses may vary between locations depending on local hydrogeological conditions. Application of the framework should therefore be supported by appropriate site investigations and numerical groundwater-flow analyses.

Nevertheless, the conceptual approach provides a useful basis for understanding the mechanisms through which hydraulic barriers influence groundwater systems and offers a transferable methodology for evaluating containment performance across a wide range of hydrogeological settings.

5.5 Future Research

Future research should focus on integrating conceptual groundwater-containment frameworks with site-specific numerical simulations and field monitoring data. Additional investigations examining the

influence of geological heterogeneity, transient recharge conditions, climate variability, and long-term barrier performance would further improve understanding of cutoff-curtain effectiveness.

There is also value in developing quantitative performance indicators that combine seepage reduction with broader hydrogeological responses, including groundwater-head redistribution, residence time, hydraulic connectivity, and flow-path modification. Such integrated metrics may provide a more comprehensive basis for evaluating groundwater-containment systems and optimising future barrier designs.

6. Conclusions

This study evaluated the effectiveness of cutoff curtains as groundwater-control measures using a comparative hydrogeological assessment framework. The results demonstrate that cutoff curtains influence groundwater systems through multiple interacting mechanisms rather than through seepage reduction alone. The installation of a cutoff curtain increases hydraulic resistance, modifies groundwater-flow pathways, redistributes hydraulic heads, and reduces hydraulic connectivity within the groundwater system.

Progressive implementation of hydraulic-control measures resulted in improved containment performance. While liner systems reduced vertical seepage, the addition of a cutoff curtain provided further containment benefits by restricting lateral groundwater migration and increasing groundwater residence times. The combined containment scenario consistently produced the highest level of groundwater control, demonstrating the advantages of integrated containment systems over individual engineering measures implemented in isolation.

The findings highlight the importance of considering broader hydrogeological responses when evaluating cutoff-curtain performance. Groundwater mounding, hydraulic-head redistribution, flow-path modification, and changes in hydraulic connectivity were identified as important indicators of containment effectiveness. Consequently, assessment of cutoff curtains should extend beyond traditional seepage-based performance measures to include a more comprehensive evaluation of groundwater-system behaviour.

From a practical perspective, the study confirms that cutoff curtains can serve as effective groundwater-management tools for applications including dams, tailings storage facilities, mine-water management systems, waste-containment facilities, and groundwater-protection projects. Their effectiveness is maximised when incorporated within integrated hydraulic-containment systems that combine multiple groundwater-control measures.

The conceptual framework presented in this study provides a transferable approach for evaluating groundwater-containment performance across a range of hydrogeological settings. Future investigations should incorporate site-specific numerical modelling, field monitoring, and long-term performance

assessment to further improve understanding of cutoff-curtain behaviour under varying geological and hydraulic conditions.

Declarations

Competing Interests

The author declares no competing interests.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Clinical trial number

Not applicable

Funding

No specific funding was received for this research.

Author Contribution

Y.Y. conceptualized the study, developed the methodology, conducted the analysis, interpreted the results, prepared figures and tables, wrote and revised the manuscript, and approved the final version.

Acknowledgements

The author acknowledges the contribution of previous hydrogeological investigations, groundwater modelling studies, environmental assessments, and professional groundwater-engineering experience that helped shape the concepts discussed in this paper.

Data Availability

All data generated or analysed during this study are included in this published article.

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Figures

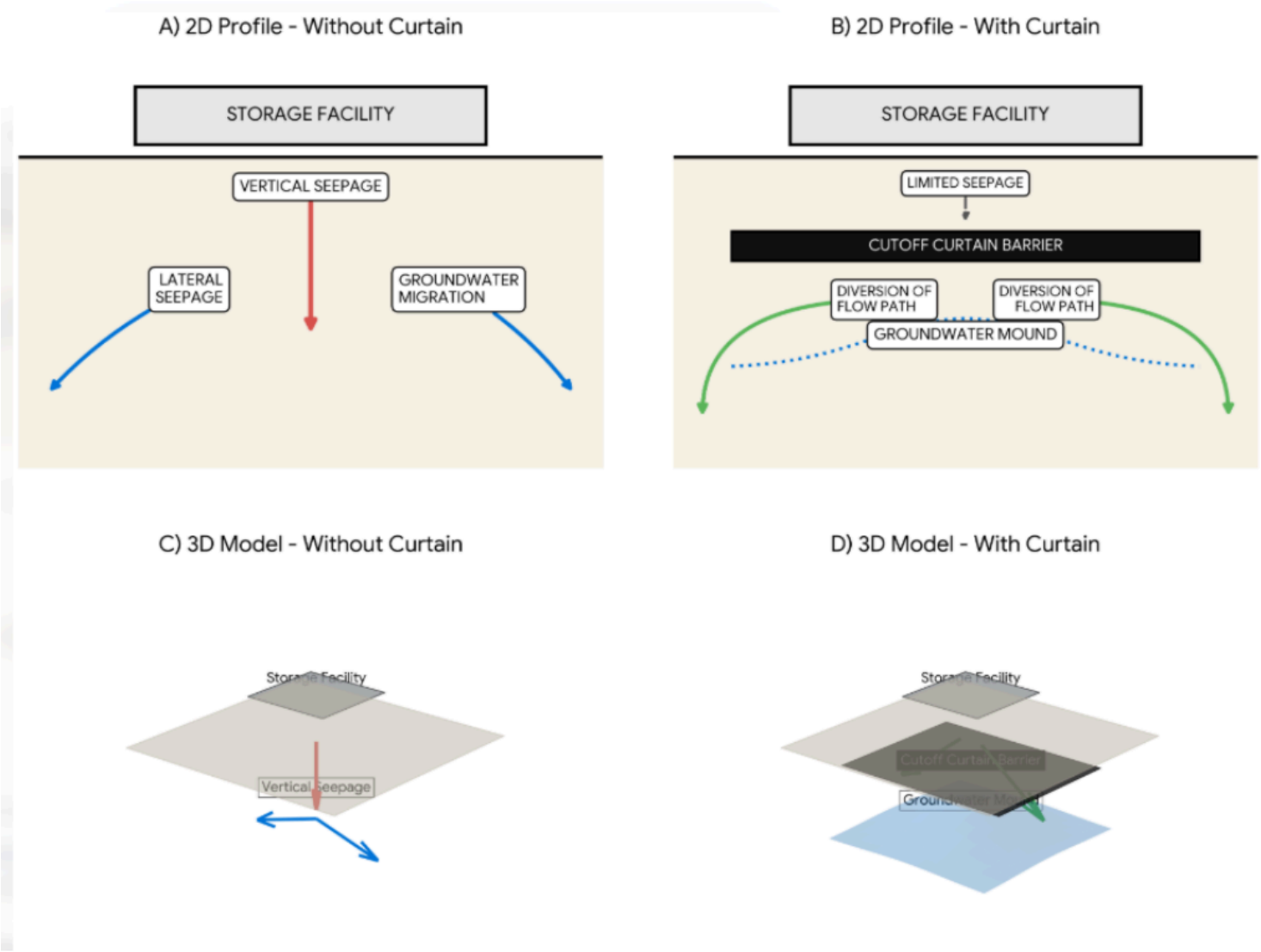

Figure 1

Conceptual groundwater-flow system showing seepage behaviour before and after installation of a cutoff curtain.

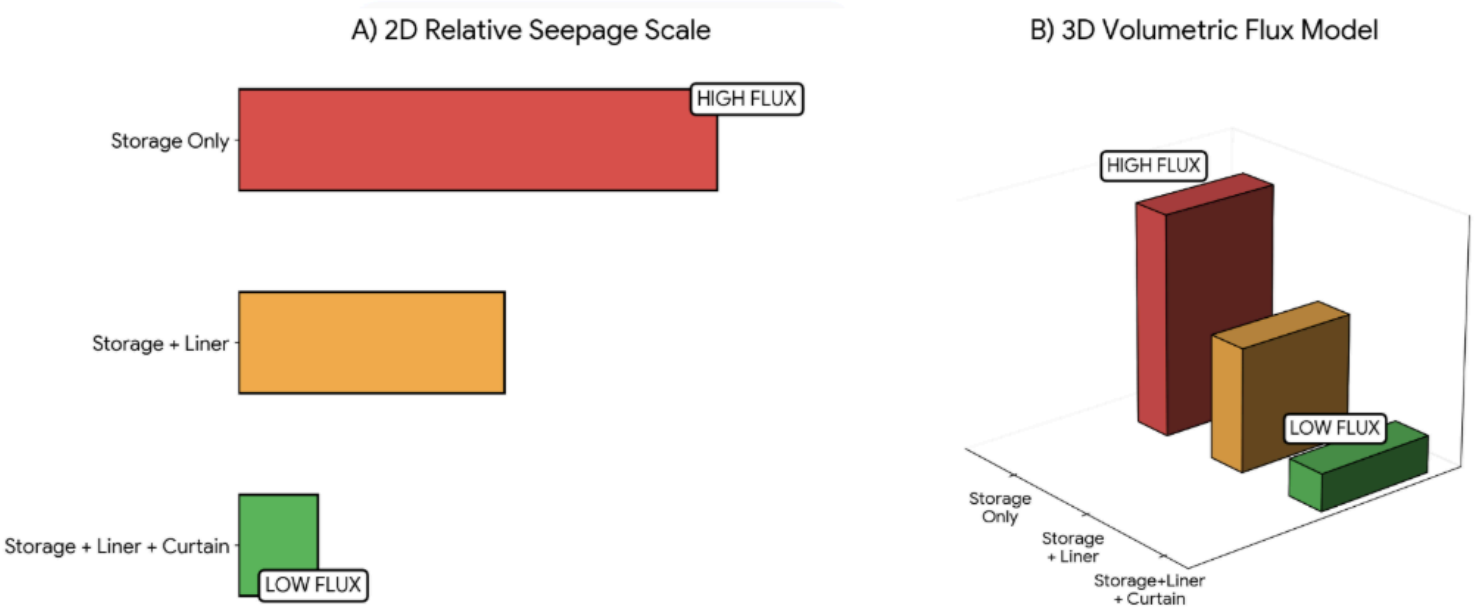

Figure 2

Relative reduction in seepage flux associated with progressive implementation of hydraulic-control measures.

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