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HYDRAULIC CONDUCTIVITY ESTIMATION FOR BALLASTED RAILWAY TRACKS: A SYSTEMATIC REVIEW

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Abstract

The hydraulic conductivity of railway ballast is a critical parameter governing track stability and longevity. It is severely compromised by ballast fouling, which accelerates water retention and embankment soil degradation. To address a historical decade scarcity of consolidated research, this systematic literature review synthesizes a comprehensive range of available evaluation methodologies across laboratory, field, and numerical paradigms. Following PRISMA guidelines, a systematic database search of Scopus (n = 49) and Web of Science (n = 106) yielded 155 original records. After duplicate removal, 123 records were screened, and 24 full-text reports were assessed for eligibility. Incorporating 2 additional papers from citation searching, a final dataset of 26 publications was selected for rigorous data extraction. The reviewed methodologies primarily comprise laboratory techniques (n = 19) and numerical simulations (n = 5). Synthesized findings demonstrate a substantial reduction in ballast drainage capacity with increasing fouling, a transition from non-linear to linear flow regimes as aggregates degrade, and a significant structural dependence on fouling type and initial aggregate gradation. Crucially, the review maps critical hydraulic parameters—specifically hydraulic conductivity, free surface dynamics, fluid flow behaviors, and permeability—across a global framework of international scientific interest, aligning findings with standards and guidelines from the USA, Australia, Europe, South Africa, Nigeria, and India. Ultimately, this study bridges a vital knowledge gap by positioning railway infrastructure as an integrated filtering and retention facility functioning as a Nature-Based Solution (NBS). To advance the field, a numerical simulation framework is proposed to synthesize both established and emergent parameters, incorporating complex aggregate geometries and time-variant hydraulic conditions for future infrastructure design.

Keywords: railway ballast; runoff; flooding; hydraulic conductivity; systematic literature review.

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1. Introduction

Thailand demonstrates the global trend through its strategic investment in a national High-Speed Rail (HSR) network, which is set to significantly transform the nation's logistical framework. This initiative is strengthened by substantial international and domestic programs, including notable projects such as the Belt and Road Initiative (BRI) high-speed link, connecting Thailand with Laos and China, and the Eastern Economic Corridor (EEC) line, designed to link major airports with key industrial centers [1–3]. Such railway lines fundamentally modify existing topographic and hydrological systems, leading to the creation of new, artificial watersheds that intercept, concentrate, and redirect both surface and subsurface water flows. The risk of soil degradation and water pollution has been noted in relation to railway construction [3].

Consequently, the overall ecological impact of railway transport is widely underestimated and is notably underrepresented in contemporary scientific literature [4]. This lack of attention is exacerbated by the fact that monitoring of stormwater runoff from railway facilities is currently inadequate

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across numerous geographical regions [5]. Due to an insufficient volume of conducted research, the precise mechanisms and routes of pollutant migration originating from railway infrastructure, particularly concerning the infiltration of significant metals into deeper soil layers, remain largely unknown [6]. The quantification of surface and filtration wastewater is inherently difficult due to the linear and geographically extended nature of railway infrastructure, and the compounded problem of synergistic environmental effects from related pollutants remains poorly understood, demanding further detailed investigation [7]. The existence of contaminants in adjacent soil validates the migration of pollutants from railway sources, as research confirms the substantial infiltration of metals into the lower layers of the embankment from runoff, which includes filtration flow [6]. Furthermore, water discharge from railway tunnels presents an environmental risk by potentially disrupting the local groundwater balance, while accumulated pollutants from the infrastructure are known to migrate to deeper soil horizons where they subsequently accumulate within groundwater reserves [8]. The release of heavy metals as friction-induced aerosols is widely recognized for causing severe, pervasive pollution that affects the atmosphere, surface water, groundwater, and the roadside soil [9]. Despite widespread acknowledgement in numerous studies that railway infrastructure is a significant source of pollution for surface water, groundwater, and soil, a considerable and consistently noted research gap persists concerning the precise mechanisms, pathways, and overall quantification of this runoff pollution and its environmental fate.

High-speed railway systems comprise various track structures, primarily categorized into traditional ballasted tracks and non-ballasted (concrete-based) slab track systems [1, 2]. Despite the continuous development of rigid slab infrastructure, the scope of this study is clearly defined as being strictly limited to ballast-based track systems. This system—consisting of rails, rail pads, sleepers, fasteners, and a highly permeable foundational ballast layer—remains the most widely utilized configuration globally and plays a critical role in track stability and water drainage [1].

The scope is explicitly clarified to encompass the ballasted railway track across all track operational conditions. Because of a recognized lack of comprehensive sources isolating specific transit phases, all operational cases—ranging from non-operational pre-functional stages to fully active high-speed transit operations—are welcomed and integrated into the evaluation. Furthermore, the investigation specifically centers on the runoff flow through the ballasted track, as this hydrological routing acts as the primary pathway for the entrainment and migration of heavy metals, herbicides, and other operational contaminants into the surrounding ecosystem.

Estimating the hydraulic conductivity of railway ballast is a complex task driven by the material's inherently large particle size, high macro-porosity, and susceptibility to changes from long-term compaction and fouling [4]. Accurately characterizing this hydraulic conductivity is absolutely critical, as it directly dictates the rate and volume of runoff flow through the ballast layer, thereby heavily influencing the potential contamination of the underlying soil and groundwater beneath the railway system [2, 3]. To evaluate this parameter, current estimation techniques are broadly classified into three categories: field measurements that capture in-situ representativeness, laboratory-based experiments providing high precision and variable control, and numerical computer simulations that yield unparalleled pore-scale insights. Understanding the inherent trade-offs among these methodologies is essential for accurately quantifying how swiftly surface water—and its dissolved pollutants—infiltrates the subsurface.

This review study aims to serve as the initial confirmatory step for aligning railway runoff issues with sustainable development paradigm. This is achieved by systematically identifying and critically evaluating current approaches for estimating ballast hydraulic conductivity. By synthesizing knowledge from across multiple disciplines, the review establishes the necessary framework for subsequent numerical simulation to validate the ballast layer's potential as a sustainable runoff management facility.

2. Materials and methods

2.1. Systematic literature review

A systematic literature review (SLR) represents a rigorous and structured approach to synthesizing existing knowledge, distinguishing itself from traditional reviews through its explicit and systematic methodology [10]. This method articulates a replicable process for collecting, analyzing, and synthesizing literature, providing clear trails of what is known and unknown about a research question [11]. Primarily utilized in healthcare for informing medical decision-making, reviews are considered the highest tier among research studies when conducted rigorously and are recognized as the highest reporting standard for presenting evidence [12]. These reviews are characterized by their focused and unbiased nature, employing explicit methods for identifying and analyzing research data to provide the best available evidence for clinical practice and health policy decisions [13].

The systematic review process starts with framing a clear, well-defined, and precise research question [10, 14]. The literature search phase typically involves an information specialist to design a robust search strategy across multiple databases to ensure transparency and reproducibility, often including non-academic literature to enhance comprehensiveness [13]. Prior to screening, deduplication of records is performed, often with automated tools, to reduce workload. Screening typically occurs in two stages: title and abstract screening to remove irrelevant studies, followed by full-text screening to confirm eligibility. The final stage involves synthesizing the evidence, which can be quantitative (meta-analysis) or qualitative (narrative), followed by interpretation of findings [10].

Despite its strengths, systematic literature reviews are subject to several limitations. The entire process, especially extensive searching and dual-reviewer screening, is notably resource-intensive and time-consuming. Subjectivity and potential for bias remain concerns, particularly if blinding is not maintained during screening, or if researcher judgment influences selection and interpretation. For instance, unclear eligibility criteria, differences in reviewer judgment, inadequate training, or the complexity of the topic can lead to low inter-rater reliability and increased conflicts. The design of the search strategy itself can introduce bias, for example, if certain topics are over-represented due to hand-searching methods, or if search strings are too rigid and exclude relevant studies [11]. Furthermore, while systematic literature review aim for exhaustiveness, practical considerations such as database access limitations (e.g., PubMed's lack of proximity searching or reliance on commercial subscription databases) can hinder achieving comprehensive results [14]. The quality of primary studies found can also be a significant limitation, leading to cautious interpretation of findings [10]. Finally, challenges arise in synthesizing a large volume of diverse papers, and a consistent finding in some fields is the lack of in-depth synthesis, particularly interpretive or explanatory approaches, potentially linked to insufficient methodological refinement in this area. The exclusion of non-academic literature, which can offer different perspectives, also limits the completeness of some systematic literature reviews [15].

2.2. Hydraulic conductivity

Estimating the hydraulic conductivity of railway ballast is a complex task due to the material's large particle size, high porosity, and susceptibility to changes from fouling and compaction. The methodologies can be broadly classified into three categories: field measurements, laboratory-based experiments, and computer simulations. The choice of method involves a fundamental trade-off between the representativeness of the measurement, the degree of control over experimental variables, and the overall cost and complexity of the procedure. Field methods excel in representativeness but lack control, laboratory methods offer excellent control but suffer from a lack of representativeness due to sample disturbance, and simulations provide unparalleled insight at the micro-scale but at a high computational cost.

Field techniques are designed to measure hydraulic conductivity directly within the track environment, thereby capturing the effects of the in-situ stress state, layering, compaction history, and large-scale heterogeneity. These methods are generally considered to provide the most representative values for actual track performance.

Laboratory methods involve testing ballast samples in a controlled environment, which allows for high precision and the systematic investigation of how factors like fouling content, density, and hydraulic gradient affect hydraulic conductivity.

Numerical methods use computational power to solve the governing equations of fluid flow within a digital representation of the ballast structure. These approaches can provide insights at the pore-scale that are unattainable through physical experiments.

The inherent complexities and trade-offs associated with the methodologies used to determine railway ballast hydraulic conductivity make a systematic evaluation necessary.

The current study employs a systematic literature review to methodically collect, identify, and critically analyze the relevant body of research. The approach adheres to a structured and replicable process to ensure transparency, minimize bias, and produce reliable and comprehensive results. A set of search strings was developed to effectively identify pertinent studies. Subsequently, introduced inclusion and exclusion criteria were applied to refine the initial dataset, ensuring its relevance to the research objectives. To further enhance the comprehensiveness of the review, backward and forward citation searches were conducted to capture related studies that may not have been identified in the initial database search. Key information from the selected papers was then systematically extracted and organized. Finally, the extracted data were critically analyzed and synthesized to address the core objectives of this review. This explicit and structured process ensures efficiency in generating dependable results.

2.3. Paper collection

Table 1. Search query

Digital library	Combined search terms
Scopus, Web of Science	(rail OR railway OR railroad OR railroads OR infrastructure OR ”high-speed rail” OR ”high-speed railway” OR ”high-speed railways” OR ”high speed rails” OR ”high speed railways” OR HSR) AND (“railway ballast” OR ”ballasted track” OR ”crushed rocks”) AND (drainage OR hydrology OR hydraulic OR ”hydraulic conductivity” OR filtration OR runoff OR ”water management” OR ”storm water” OR rain OR rainfall OR precipitation OR ”water flow” OR ”fluid flow” OR ”liquid flow” OR porosity OR ”porous media” OR permeability)

The literature search was conducted utilizing the Web of Science (WoS) and Scopus digital libraries, which are widely regarded as premier multidisciplinary databases providing comprehensive access to peer-reviewed journals. A search query (Table 1) was formulated based on three primary concepts: “hydraulic conductivity,” “railway,” and “ballast,” which were grouped with their corresponding synonyms. This procedure yielded an initial corpus of 155 papers as depicted in Fig. 1.

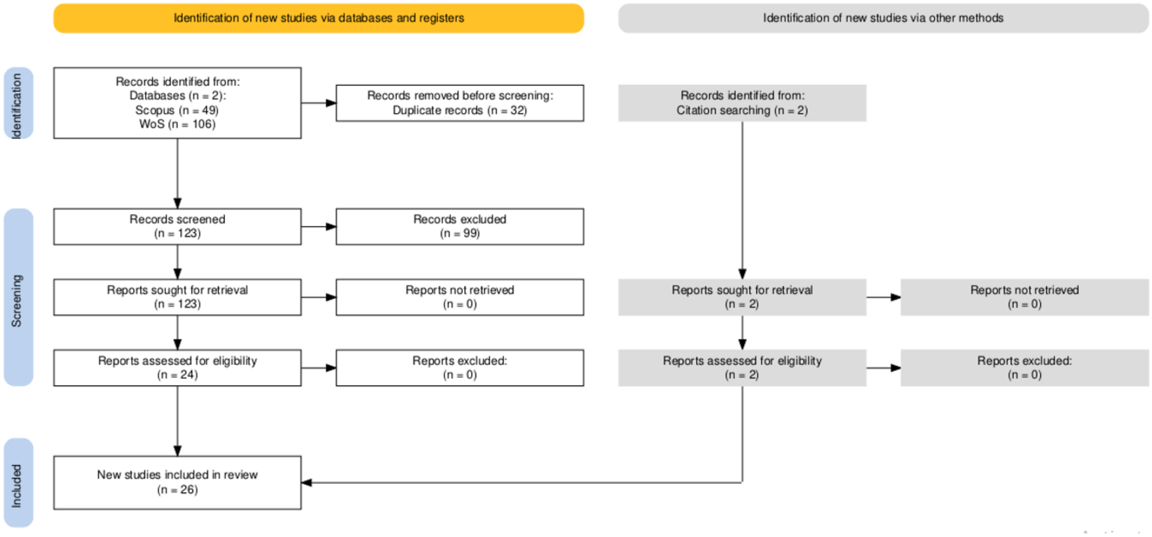

Figure 1. PRISMA flow diagram [16]

A set of predefined inclusion and exclusion criteria, outlined in Table 2, was established to screen the initial findings. The application of these criteria, in conjunction with the elimination of duplicate entries, refined the selection to 24 publications [17–40].

Table 2. Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion	Method
Access	open access	limited access	web filter
Language	English	non-English	web filter
Scope	runoff flow through railway track ballast volume with retention and further discharge out of the granular layer	out of the scope	manual screening
Keywords	water; precipitation; rain; rainfall; runoff; floods; flow; fluid; liquid; hydraulic; hydraulic conductivity; retention; capacity; drainage; permeability; porosity	mechanical; structural; stability; stress; tension; shear; concrete; modulus; vibration; cement; acoustic; sound; thermal; marine; ship	manual screening

To ensure a comprehensive search, no time-based constraints were applied, and both backward and forward citation tracking was performed to minimize the risk of omitting relevant studies. This process yielded 2 additional relevant papers that met all inclusion criteria but were not captured by the initial keyword strings in Scopus and WoS [41, 42].

The initial database search was executed on July 11, 2025. Following the retrieval of raw records, duplicate-removal process merged identical entries and eliminated overlapping documents to establish a clean baseline dataset. The remaining articles were subjected to a primary screening phase, during which their titles, abstracts, and keywords were evaluated against predefined inclusion and exclusion criteria. Documents meeting these initial benchmarks advanced to a rigorous full-text eligibility assessment, where the complete manuscripts were analyzed to confirm their relevance. To guarantee methodological integrity, the entire screening and evaluation pipeline was conducted independently by three reviewers. Disagreements regarding study eligibility or potential risk of bias were resolved through structured collaborative discussions until a mutual consensus was reached. For the subsequent data-extraction protocol, the primary author extracted the relevant datasets, which were then systematically reviewed by the second author and validated by the remaining co-authors to ensure rigorous accuracy and cross-dataset consistency.

2.4. Data extraction

The collected papers were accurately reviewed to extract the necessary information. Key data points were organized into a structured table, including the year of publication, geographical distribution, research objectives, the specific methodology for estimating hydraulic conductivity (e.g., field, laboratory, simulation), the techniques employed (e.g., constant head permeameter, Finite Element Method) and key findings.

To mitigate systematic bias and ensure a reproducible workflow, this screening and evaluation process was strictly anchored to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [16]. Reviewers evaluated and compared the candidate studies against predefined quality metrics and a highly specified set of inclusion and exclusion criteria in Table 1 to determine their suitability for final data synthesis. The inclusion criteria were established by identifying the highest-frequency technical terms utilized within the core literature of the targeted field. However, due to a pronounced scarcity of primary literature directly addressing the specific domain, initial keyword queries frequently retrieved documents from adjacent engineering disciplines—including civil, mechanical, electrical, acoustic, and marine engineering—that employ overlapping terminology. Consequently, the exclusion criteria were precisely calibrated to filter out non-related studies arising from such semantic ambiguity. For example, specific boundary constraints were implemented to differentiate between identical descriptors across disciplines, such as distinguishing ”railway ballast” in structural transportation engineering from ”ballast water” in marine engineering, thereby ensuring the final synthesis remained strictly focused on the intended domain.

3. Results and discussions

3.1. Distribution of published papers by year and research team

The papers included in the review were published from 2009 to 2025. An increase was observed from 2023 which could probably demonstrate rising interest in the subject as depicted in Fig. 2.

The studies were conducted in various global regions with definite numbers of works related to Iran (8 papers) research group (Table 3). Visual geographical distribution summary is presented in Fig. 3.

Research methods related to laboratory experiments (16 papers) estimated resulting ballast hydraulic conductivity with various grain size, shape distributions, fouling material, fracture, percentage, inflow height, velocity. Numerical simulations (14 papers) employed developed models to predict or validate hydraulic conductivity, free surface, laminar or turbulent flow regimes.

Five papers combined laboratory experiments with further computer simulation. Two studies [34, 38] focused on reviewing analysis of previously developed research. One study developed field tests of the ballast layer deformation under cyclic dynamic railway operations loads [40].

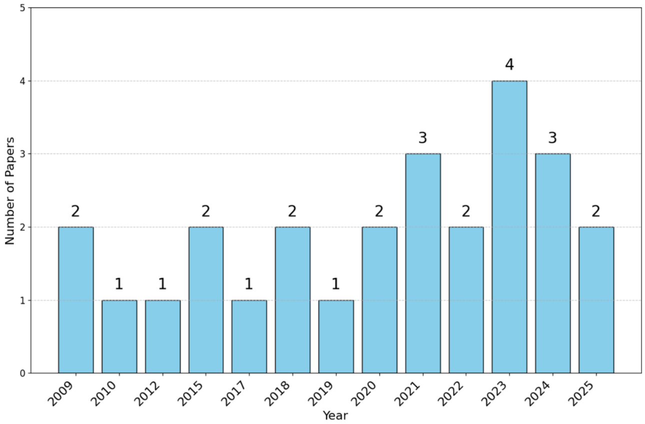

Figure 2. Articles published by year

Table 3. Papers by authors

Authors	Country	Institution	Papers
Mehdi Koohmishi	Iran	Department of Civil Engineering, Faculty of Engineering, University of Bojnord	6
K. R. Rushton	United Kingdom	School of Engineering, University of Birmingham	3
Michael H. Meylan	Australia	School of Mathematical and Physical Sciences, The University of Newcastle	1
Scott Schmidt, Erol Tutumluer	USA	University of Illinois Urbana-Champaign	2
Mehdi Koohmishi, Yunlong Guo	Iran; Netherlands	University of Bojnord; Delft University of Technology	2
Raed Alrdadi, Michael H. Meylan	Australia	The University of Newcastle	3
J.I. Shu, Y. Wang	USA	University of South Carolina	2

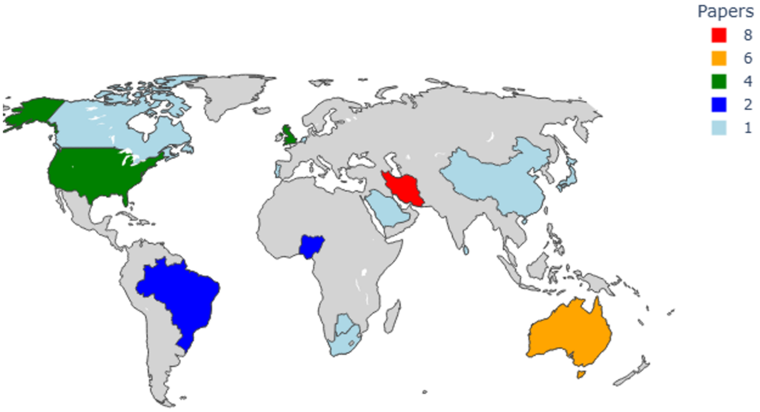

Figure 3. Included articles geographic distribution

3.2. Techniques and parameters

Table 4 provides a structured synthesis of the research methods and principal hydraulic parameters examined across the 26 studies included in the present systematic literature review (references [17–42]). For each reviewed publication, the table identifies the type of investigative approach employed – classified into three methodological categories: field studies (F), laboratory experiments (L), and numerical or computational simulations (S) – thereby enabling a comparative assessment of the methodological distribution within the reviewed body of literature. The second dimension of the table captures the primary hydraulic parameter addressed in each study, with the reviewed works collectively focusing on hydraulic conductivity, permeability, fluid flow, free surface behaviour, and water level as the principal quantities of interest.

Table 4. Employed methods and main hydraulic parameters

Reference	F	L	S	Main parameters
[41]			■	free surface
[42]			■	fluid flow; free surface
[17]		■	■	hydraulic conductivity; free surface
[18]			■	fluid flow
[19]		■		hydraulic conductivity
[20]		■		hydraulic conductivity
[21]			■	permeability
[22]			■	hydraulic conductivity
[23]		■	■	hydraulic conductivity; permeability
[24]		■		hydraulic conductivity
[25]		■		hydraulic conductivity
[26]			■	hydraulic conductivity; permeability
[27]		■		hydraulic conductivity
[28]		■		hydraulic conductivity
[29]		■		hydraulic conductivity
[30]			■	permeability
[31]			■	hydraulic conductivity; permeability
[32]			■	hydraulic conductivity; free surface
[33]			■	permeability
[34]		■		permeability
[35]			■	hydraulic conductivity; water level
[36]		■		hydraulic conductivity
[37]			■	hydraulic conductivity; water level
[38]			■	fluid flow
[39]		■	■	fluid flow; permeability
[40]	■	■		hydraulic conductivity

Considering laboratory techniques employed in 19 studies, constant-head permeability method with other equipment was used to provide water inflow or cyclic loading conditions. Individual studies used specific equipment: open channel flow apparatus [39] or thermal camera [38], impact loading testing apparatus [25], system for rainfall imitation [36].

Numerical simulation approaches demonstrated modifications of Finite Element Method (FEM)

(5 papers), Analytical-Numerical models (3 papers), Numerical model with Dupuit–Forchheimer approximation (1 paper) or machine learning [35] and machine vision [21].

A notable gap in the reviewed literature is the lack of studies employing advanced, pore-scale Computational Fluid Dynamics (CFD) techniques. While many studies utilized numerical modeling, they predominantly relied on macroscopic approaches like the Finite Element Method (FEM) with Darcy, Dupuit-Forchheimer, or Forchheimer laws to approximate flow through a porous medium.

A cross-reference search revealed that source [36] contains a bibliographic entry (listed therein as reference [37]) corresponding to the work titled ”Multi-Phase Flow Simulation for Transient Analysis of Ballast Drainage Behavior and Shoulder Cleaning Effect” [42]. This study presents a computational methodology for quantifying trapped moisture within fouled and moderately fouled ballast layers, wherein water inflow is modelled through the random injection of rain droplets as a representation of rainfall. Given that the underlying rainfall generation process is not developed within the aforementioned paper but is instead derived from an external source, the paper describing the rainfall generator algorithm has been additionally identified and incorporated into the review [41] to ensure methodological traceability and completeness of citation.

Both papers utilized pore-scale Computational Fluid Dynamics (CFD) with the Volume of Fluid (VOF) method to model multiphase liquid-gas interfaces. Shu, J. I. and Wang, Y. [41] introduced a novel adaptive mesh refinement (AMR) model and a pseudo-random algorithm for discrete droplet injection. Paper [42] integrated the Darcy-Forchheimer equation to simulate the flow resistance caused by fouling materials within ballast layers.

3.3. Ballast

The American Railway Engineering and Maintenance of Way Association (AREMA) publishes recommended practices for the design, construction, and maintenance of railway infrastructure, primarily for the North American rail industry. AREMA No. 3, No. 4, No. 24, and No. 25 were commonly used, alongside variations such as AREMA No. 4A [23, 25, 35].

Ballast specifications generally demand a uniform gradation, typically defined by a uniformity coefficient (C_u) ranging from 1.5 to 3.0. A clean ballast sample (AREMA No. 3) used specific sizes $d_{\max} = 50.0$ mm and $d_{\min} = 25.0$ mm. Specific values for AREMA gradations used include $C_u = 1.47$ (No. 3), $C_u = 1.31$ (No. 4), and $C_u = 2.75$ (No. 25) [35, 40].

A clean ballast sample (AREMA No. 3) used specific sizes $d_{\max} = 50.0$ mm and $d_{\min} = 25.0$ mm. Another gradation (AREMA No. 25) utilized $d_{\max} = 62.5$ mm and $d_{\min} = 4.75$ mm [35]. Australian standards specify that clean ballast aggregates should be between 63 mm and 13.2 mm [27].

Ballast samples collected from Nigerian railway tracks (RT1-RT5) exhibited D_{50} values ranging from 33.2 mm to 44.4 mm. Clean ballast samples were typically uniformly graded and often classified as Poorly Graded Gravel. The presence of fine particles due to fouling or degradation shifts the ballast gradation curves towards a broad-graded classification [25, 29].

Paper [42] specifically modeled clean and fouled ballast using uniform circular aggregates with a diameter of 25.4 mm. The study analyzed Fouling Indices (FI) of 7.4 and 23, and evaluated three fouling profiles (1/3, 2/3, and 3/3 depth). Paper [41] used a 3-layered ball pyramid (30 mm diameter balls) as a base geometry to verify droplet dispersal and interface capturing.

The physical shape of ballast particles is critical, especially when considering degradation and its effect on drainage [21]. The ballast layer was ideally composed of highly angular granular aggregates [17]. Degradation occurred primarily due to abrasion and particle breakage [21, 25], leading to fragmentation and a morphological shift [27]. Degradation tests, such as the Los Angeles Abrasion

(LAA) test, are used to simulate wear. A scatter plot comparing the Aggregate Impact Value (AIV) and LAA results exhibited a highly significant linear trend ($R = 0.992$, $R^2 = 0.9849$) [29].

Advanced methods employ machine vision technology for degradation analysis for shape descriptors in imaging. In imaging analysis, ballast particles are generally expected to have a convex or nearly-convex shape. The degree of convexity was used in conjunction with a convex-hull test to filter out non-particle segments and identify true ballast particles [21].

A central focus of the reviewed literature is the effect of fouling on ballast permeability. To quantify the degree of contamination, researchers have utilized several key indices. The Fouling Index (FI), often based on particle size distribution, was used to assess contamination levels and recommend maintenance for 4.75 to 46.04. Specific values tested include Fouling Index 1.6 to 39.0, and simulated values up to 58.7 [19, 21, 25, 27, 34, 35]. The Void Contamination Index (VCI), which relates the volume of fines to the void volume of the clean ballast, was also a critical parameter for evaluating the reduction in drainage capacity. Void Contamination Index (VCI) assumed 0% (clean ballast), 25%, 50%, 75%, and 100% [17, 18, 22, 26, 32, 40]. Other studies refer more generally to the Fouling Ratio (FR), typically as a percentage, to describe the proportion of fouling material like clay, sand, or rock dust mixed with the ballast [20, 23, 25, 28, 30, 35, 36]. Reliability analysis suggests that fouling ratios of 40% (sand-fouled) and 20% (clay-fouled) represent critical conditions affecting drainage potential.

3.4. *Domain geometry*

Large-Scale permeameters with cylindrical chambers used for constant head tests to measure hydraulic conductivity with chambers varied: 500 mm diameter × 1000 mm height [20]; 460 mm diameter × 720 mm height [40]. Large diameters were used to minimize boundary effects [20, 23].

Large-scale flume apparatus used to simulate drainage under controlled rainfall and measure water height/free surface location. Typically represents a half-sized cross-section of the ballast layer [22, 33]. Dimensions: 2.0 m length, 0.6 m width, and 0.6 m height [22, 35, 36].

University of Illinois Constant Head Aggregate Permeameter (UI-CHAP) designed to test large aggregates with a sample box size of 30.5 cm × 30.5 cm × 61 cm (1 ft. × 1 ft. × 2 ft.), measuring horizontal permeability [21, 34].

Two-dimensional trapezoidal geometry used to model realistic railway ballast dimensions for seepage and flow analysis, assuming symmetry (half-track) [17, 22, 26, 32, 33].

Multi-layer trapezoid cross-sections included up to four layers representing different fouling levels or distinct components as ballast, sub-ballast, shoulder [17, 31]. Model 1 with 2 horizontal layers: clean top, fouled bottom; Model 2 with 3 equal horizontal layers; and Model 3 with 3 equal layers plus independent shoulder layer [17].

Rectangular dam as porous media used primarily for validation of seepage analysis techniques against theoretical results [18, 30].

Representative Volume Element (RVE) for particle-based simulations was used in Discrete Element Modeling [17, 33, 35].

Paper [41] employed a 2-D long rectangular domain (0.045; 15) and a 3-D domain (0.1; 0.1; 0.4). Paper [42] utilized a 2-D half-track cross-sectional geometry with a 2.5 m length, 1.0 m height, and a 2 : 1 shoulder slope.

3.5. *Hydraulic parameters*

Clean railway ballast, composed of uniformly graded and highly angular coarse aggregates, is designed to possess substantial large pore structures that facilitate rapid and efficient subsurface drainage. Experimental measurements demonstrate that the saturated hydraulic conductivity of clean ballast is remarkably high, often reported in the range of 30 cm/s to 31 cm/s.

However, due to the large size of the interconnected voids, water flow through clean ballast is highly turbulent and does not conform to the linear assumptions of Darcy's law (Eq. (1)).

$$V = k \cdot \frac{\Delta h}{L} = k \cdot i \tag{1}$$

where V is the discharge or flow velocity (m/s or cm/s), k is the hydraulic conductivity coefficient (m/s), Δh is the hydraulic head loss (m), L is the length of the porous specimen in the flow direction (m) and i is the applied hydraulic gradient.

Instead, the relationship between discharge velocity and the hydraulic gradient exhibits a nonlinear, non-Darcian behavior that is mathematically best characterized by a power law equation, such as Izbash/Missbach (Eq. (2)).

$$i = a \cdot V^b \tag{2}$$

where i is the hydraulic gradient, V is the discharge/water flow velocity (m/s) and a, b are experimental coefficients.

Two parameter quadratic model/Forchheimer's law is used to capture non-Darcian, turbulent, or transitional flow regimes through porous materials by incorporating an inertial term (Eq. (3)).

$$i = a \cdot V + b \cdot V^2 \tag{3}$$

where i is the hydraulic gradient, V is the discharge velocity (m/s) and a and b are experimental coefficients.

As the hydraulic gradient increases, inertial forces and momentum transfer become significant, resulting in higher resisting forces and a flow rate increment that is consistently lower than what a linear Darcian model would estimate.

The accumulation of fine particles—such as clay, coal dust, or intruding subgrade soil—within the void spaces of the ballast matrix, a process known as fouling, drastically alters its physical and hydraulic properties. Fouling significantly restricts the free-draining capacity of the track, reducing hydraulic conductivity by several orders of magnitude even at relatively low contamination percentages. As the large interstitial voids become progressively congested with fine materials, the internal flow paths narrow, which actively suppresses the turbulence of the percolating water.

Consequently, the flow regime transitions from a turbulent, non-Darcian state to a highly restricted laminar flow. Under these severely fouled conditions, the velocity-gradient relationship becomes increasingly linear, meaning that the drainage behavior and hydraulic conductivity can be accurately modeled using the conventional linear principles of Darcy's law (Eq. (1)).

To accurately evaluate the time-dependent drainage performance and water table fluctuations within the track substructure, transient numerical modeling requires precise inputs for rainfall intensity, specific yield, and boundary conditions. Rainfall intensity acts as the primary external forcing parameter that dictates the volumetric flow rate entering the domain, critically influencing the maximum water table elevation and the onset of potential track saturation. Specific yield, which defines the drainable porosity of the materials, is mathematically essential for unsteady-state simulations as it governs the rate at which water is released from storage and dictates the time required for the free surface to recede after precipitation ceases. Furthermore, accurately defining boundary conditions—such as the track bed slope, downstream drainage ditch water levels, and the inclusion of an iterative free-surface boundary—is paramount for capturing the authentic multidimensional seepage faces, shedding mechanisms, and precise transient outflow rates from the ballast structure.

Table 5 summarizes the primary hydraulic parameters utilized across the reviewed studies, the specific conditions under which each study was conducted, the relevant outcomes within the scope of this review, the corresponding units of measurement, and brief comments explaining the implications. All abbreviations utilized in Table 5 are defined in Table 6.

Table 5. Hydraulic parameters

No.	Param.	Condition	Reported range/value	Unit	Ref.	Implication
1	k	CB	0.43	m/s	[1]	If VCI > 46%, mandates maintenance
2		VCI = 25; 100%	∇90.72; 99.96%	%		
4	SY	unsteady-state	0.2	L/m^3	[2]	Overflow if continuous flooding
5	k	CB	0.3	m/s		
6	Γ	CB	$\nabla\nabla$	m		
7	Fv	k $\nabla\nabla$	> 80	%	[3]	Mandates maintenance
8	k	broadly-graded ballast	∇	n/a	[4]	CB k is lower for more broadly-graded ballast; Sand-fouled k is low vs CB; fine sand k is 10x lower than coarse sand k; If Δ, k of initial gradations approaches the same value
9		AREMA No.3; uniformly graded ballast	Δ	n/a		
10		Sand	10^{-2}–10^{-3}	m/s		
11		basalt; CB; AREMA No. 3	0.0293	m/s		
12		basalt; CB; AREMA No. 24	0.023	m/s		
13		basalt; CB; AREMA No. 25	0.0174	m/s		
14		marl; CB; AREMA No. 3	0.0321	m/s		
15		marl; CB; AREMA No. 24	0.0208	m/s		
16		marl; CB; AREMA No. 25	0.0174	m/s		
17		dolomite;CB; AREMA No.3	0.02	m/s		
18		dolomite;CB; AREMANo.24	0.0167	m/s		
19		sandstone; CB; AREMA No. 3	0.0345	m/s		
20		sandstone; CB; AREMA No.24	0.0324	m/s		
21		coarse sand; FR 20-80%; AREMA No. 3	$(0.0144; 6.2 \cdot 10^{-3})$	m/s		
22		coarse sand; FR 20-80%; AREMA No. 25	(0.0118; 0.0058)	m/s		
23		fine sand; FR 20-80%; AREMA No. 3	$(4.23 \cdot 10^{-3}; 7 \cdot 10^{-4})$	m/s		
24		fine sand; FR 20-80%; AREMA No. 25	$(3.51 \cdot 10^{-3}; 6.2 \cdot 10^{-4})$	m/s		
25	V	FI; i	∇	cm/s	[5]	V vs i flow trend follows a nonlinear power curve

No.	Param.	Condition	Reported range/value	Unit	Ref.	Implication
27	β_K	k = random; AREMA no. 3; CB	> 9.0	n/a	[6]	reliable
28		k = random; VCI $>$ 60%; AREMA no. 3	$\nabla\nabla$	n/a		unreliable
29	H	AREMA no. 24; FI;		cm	[7]	high sand-fouled ballast remains acceptable
31	k	AREMA No. 3; CR = 0%	2.93	cm/s	[8]	even severely rubberized ballast specimens are still acceptable (CR = 30%)
32		AREMA No. 4; CR = 0%	2.3	cm/s		
33		AREMA No. 25; CR = 0%	1.74	cm/s		
34		AREMA No. 3; CR = $10, 20, 30\%$	(1.224; 0.724)	cm/s		
35		AREMA No. 4; CR = $10, 20, 30\%$	(1.166; 0.516)	cm/s		
36		AREMA No. 25; CR = $10, 20, 30\%$	(1.113; 0.431)	cm/s		
38	k	AREMA No. 3; clay; FR = $20, 30, 40, 50, 60, 70\%$	(0.103; 0.002)	cm/s	[9]	asperity abrasion has an even greater impact on k; Degradation accelerates fouled ballast $k\nabla$ via clay
39		AREMA No. 25; clay; FR = $20, 30, 40, 50, 60, 70\%$	(0.319; 0.002)	cm/s		
40	k	CB	0.3	m/s	[10]	Random k increases flow; $\Gamma\nabla\nabla$ flow
41		VCI = 25%; shoulder	$3.5968 \cdot 10^{-4}$	m/s		
42		VCI = 50%	$1.7995 \cdot 10^{-4}$	m/s		
43		VCI = 100%	$9 \cdot 10^{-5}$	m/s		
44	k	soil 5.68%; liquid intrusion 10%	0.135	cm/s	[11]	Liquid intrusion has low effect on k, but topsoil inclusion %Δ causes $k\nabla$
45	k	AREMA No.3, 4, 24, 25; FR; compaction level	(0.0014; 0.0051)	m/s	[12]	Uniform subballast gradation accelerates fine particle infiltration
46	k	clay 0, 10, 20, 30%	(0.0103; 0.0044)	cm/s	[13]	$k\nabla$ by growing clay content

No.	Param.	Condition	Reported range/value	Unit	Ref.	Implication
47	k	FR; chemicals intervention	(0.02; 0.37)	cm/s	[14]	$k\nabla$ as ballast fouling increased but maintains as acceptable
48	k	sub-ballast	$7.5 \cdot 10^{-4}$	m/s	[15]	Validated with the reported experiments
49		ballast	$375 \cdot 10^{-4}$	m/s		
50	SY	sub-ballast	0.03	L/m^3		
51		ballast	0.3	L/m^3		
52	k	CB	0.34	m/s	[16]	Validated with the reported experiments
53		VCI = 5%; shoulder	0.1571	m/s		
54		VCI = 10%	0.1021	m/s		
55		VCI = 200%	0.0601	m/s		
56	k	non-linear k: FEM&time-method of characteristics	n/a	n/a	[41]	Relationship between k and PI
57	k	CB	30	cm/s	[42]	CB yields a power curve V–i trend; more degraded ballast approaches Darcy's linear sand trend
58		FI = 1.6	21	cm/s		
59		FI = 3.1	14	cm/s		
60		FI = 7.4	1.2	cm/s		
61		FI = 14	0.27	cm/s		
62		FI = 23	0.1	cm/s		
63		FI = 39-1	0.18	cm/s		
64		FI = 39-2	0.1	cm/s		
65		Sand	0.042	cm/s		
67	k	linear/non-Linear; CB; AREMA No. 3	0.422 / 0.493	cm/s	[17]	Particle gradation influences porous layer drainage potential; Nonlinear V–i model in A-N approach is crucial to match exp data
68		linear/non-Linear; CB; AREMA No. 4	0.460 / 0.537	cm/s		
69		linear/non-Linear; CB; AREMA No. 4A	0.415 / 0.454	cm/s		
70		linear/non-Linear; CB; AREMA No. 25	0.410 / 0.435	cm/s		
71		FR = 10–50%; AREMA No. 3	(0.480; 0.050)	cm/s		
72		FR = 10–50%; AREMA No. 4	(0.530; 0.070)	cm/s		
73		FR = 10–50%; AREMA No. 4A	(0.442; 0.035)	cm/s		
74		FR = 10–50%; AREMA No. 25	(0.390; 0.021)	cm/s		
75	H	clay contamination; FR	35	cm	[18]	k$\nabla\nabla$

No.	Param.	Condition	Reported range/value	Unit	Ref.	Implication
76	k	CB, upper layer	3250	m/d	[19]	Highly permeable ballast overlies sub-ballast with k at least an order of magnitude less
77		clean sub-ballast, lower layer	65	m/d		
78		dual railway lines			[20]	Sub-ballast SY&k affect the track drainage rate
79	k	CB	1	m/d		
80		CB	$1.157 \cdot 10^{-5}$	m/s		
81		clean subballast	1.73	m/d		
82		clean subballast	$2.0 \cdot 10^{-5}$	m/s		
107	q	$W = 1.00$ m, $H = 0.39$ m, $L = 0.60$ m	($1.4 \cdot 10^{-3}$; 0.0203)	m^3/m/s	[21]	Mandates maintenance
109		VCI	$4 \cdot 10^{-4}$	m/s	[22]	Mandates maintenance
110	k	CB	0.3	m/s		
113	MC	incompressible multi-phase; FI = 23	10.4	%	[23]	Severe congestion
114	RI	n/a	10	in/h		
116	RI	n/a	900	mm/h	[24]	Meshing parameters
117	V	$t = 0.005$ s	0.4	m/s		

Table 6. Abbreviations used in Table 5

No.	Abbreviation	Term / Description
1	k	hydraulic conductivity
2	FR	fouling ratio
3	VCI	void contamination index
4	FI	Selig and Waters fouling index
5	SY	specific yield
6	Δ	increase
7	∇	decrease
8	$\nabla\nabla$	substantial decrease
9	Γ	free surface
10	Fv	South-African railways fouling index
11	AREMA	American railway engineering and maintenance-of-way association
12	A-N	analytical-numerical
13	i	hydraulic gradient
14	PI	permeability index
15	V	velocity

No.	Abbreviation	Term / Description
16	q	flow rate
17	β_K	reliability index
18	CB	clean ballast
19	H	water level
20	CR	crumb rubber particles
21	MC	moisture content
22	RI	rain intensity
23	t	time

3.6. Future simulation parameters

Future computer simulations should transition from macroscopic approaches, such as the Finite Element Method (FEM) with Darcy's law approximations, toward advanced pore-scale Computational Fluid Dynamics (CFD) to address existing literature gaps. These models should utilize the Volume of Fluid (VOF) method combined with Adaptive Mesh Refinement (AMR) to accurately capture the air-water interface of discrete raindrops. Instead of simplifying the ballast as uniform circular stones, simulations should incorporate the highly angular geometries and realistic grain size distributions (such as AREMA gradations) described in laboratory studies to better represent the complex interstitial void spaces.

The simulated hydraulic environment should move beyond saturated, ”soaked” track assumptions to model transient rainfall events using a random droplet injection algorithm. This approach allows for the investigation of how water drops fall, coalesce, and migrate through ballast voids under varying rainfall intensities. To account for the reduction in hydraulic conductivity observed in field studies, the Darcy-Forchheimer equation can be integrated into the solver to represent the flow resistance and moisture retention caused by different fouling materials and contamination indices. These simulations can then quantify time-dependent moisture accumulation and the specific penetration depths required to reach the sub-ballast layer.

Future research should expand computational domains from 2-D half-track cross-sections to full 3-D geometries to capture longitudinal flow and complex boundary interactions. Simulations should specifically analyze the discharge behavior at the base of the ballast and the effectiveness of maintenance operations, such as shoulder cleaning, in reopening flow passages. By modelling the transition from clean to heavily fouled states across multi-layer domains, these simulations can provide predictive tools for determining critical fouling thresholds and optimizing drainage infrastructure.

Finally, the selection of specific simulation parameters, such as mesh density, time-step intervals, and the complexity of aggregate shapes, must be carefully balanced against available computational resources and project timelines. While high-fidelity 3D models offer superior accuracy, the increased computational cost may necessitate the use of simplified 2D representations or optimized adaptive mesh refinement strategies to ensure numerical stability and timely delivery of results without compromising the fundamental physical insights required for ballast drainage analysis.

4. Conclusions

This systematic literature review reveals a significant shift from simplified macroscopic drainage models toward high-fidelity, pore-scale Computational Fluid Dynamics (CFD) simulations. While laboratory experiments have established the fundamental impacts of fouling and rainfall intensity on ballast conductivity, numerical modeling, particularly using the Volume of Fluid (VOF) method and

Adaptive Mesh Refinement (AMR), now offers the most promising path for capturing complex transient moisture migration. The review identifies a persistent gap in full 3D longitudinal modeling and the representation of realistic aggregate angularity, suggesting that future simulations must prioritize the integration of Darcy-Forchheimer resistance with discrete droplet dynamics to accurately reflect field conditions. Ultimately, the transition from saturated, steady-state assumptions to multi-phase, multi-layer transient simulations provides a critical foundation for optimizing railway drainage maintenance and enhancing track resilience against increasing extreme weather events.

The novel synthesis newly generated by this review lies in its comprehensive integration of fragmented experimental and numerical datasets into a unified global framework. By evaluating multi-decade data alongside emergent numerical paradigms, this review identifies a definitive structural shift from simplified macroscopic drainage models toward high-fidelity, pore-scale Computational Fluid Dynamics (CFD). Specifically, the critical consolidation of advanced parameters—including the Volume of Fluid (VOF) method, Adaptive Mesh Refinement (AMR), and Darcy-Forchheimer resistance—offers a newly synthesized roadmap to address persistent gaps in 3D longitudinal modeling and realistic aggregate angularity.

As an initial data-gathering and benchmarking phase, this review does not seek to definitively alter foundational hydraulic equations; rather, its primary contribution is the systematic assembly of this global dataset to serve as the baseline for upcoming computational validation. The central hypothesis introduced by this review—positioning ballasted tracks as filtering and retention facilities operating as Nature-Based Solutions (NBS)—remains a theoretical synthesis at this stage. Fundamental validation and truly novel empirical findings are anticipated in the subsequent phase of this research, where these newly categorized pore-scale CFD simulation parameters will be rigorously tested under time-variant field conditions.

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