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Percolation, Collection and Recirculation in Heap Leaching: Hydraulic Design, Solution Chemistry Management, and System Reliability – A Critical Review

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Abstract

Heap leaching is often described as a metallurgical extraction operation, yet its practical performance depends on a hydraulic circuit that must continuously collect, equalize, condition, and recirculate percolating solutions while maintaining containment and geotechnical stability. This critical review examines percolate collection and recirculation as an integrated process system rather than as auxiliary infrastructure. The analysis links heap hydrodynamics, drainage-layer behavior, underdrain capacity, collection channels, pregnant-leach solution and raffinate ponds, solution-chemistry management, pumping reliability, irrigation return, instrumentation, and operational control. Particular emphasis is placed on the coupled consequences of solution holdup, transient infiltration, ore consolidation, preferential flow, precipitation and scaling, water-balance disturbances, pump degradation, liner leakage, and extreme rainfall. Evidence is interpreted using a performance-first framework that separates nominal design capacity from hydraulic observability, controllability, resilience, and scale-up reliability. The review shows that stable operation requires simultaneous control of liquid inventory, hydraulic head, reagent inventory, and storage margin; optimizing any of these in isolation can transfer risk elsewhere in the circuit. Recent developments in state estimation, thermal and geophysical monitoring, machine learning, and model-predictive control offer pathways toward adaptive operation, but their industrial value depends on robust sensors and validated physical constraints. This paper proposes a practical design framework in which conservative hydraulic sizing, drainage redundancy, emergency storage, chemical conditioning, pump duty management, and closed-loop monitoring are treated as interacting barriers to loss of hydraulic control. The resulting perspective reframes collection and recirculation as a core determinant of recovery, reagent efficiency, environmental performance, and heap-leach facility reliability.

Keywords: heap leaching; percolate collection; raffinate recirculation; hydraulic design; solution chemistry; system reliability.

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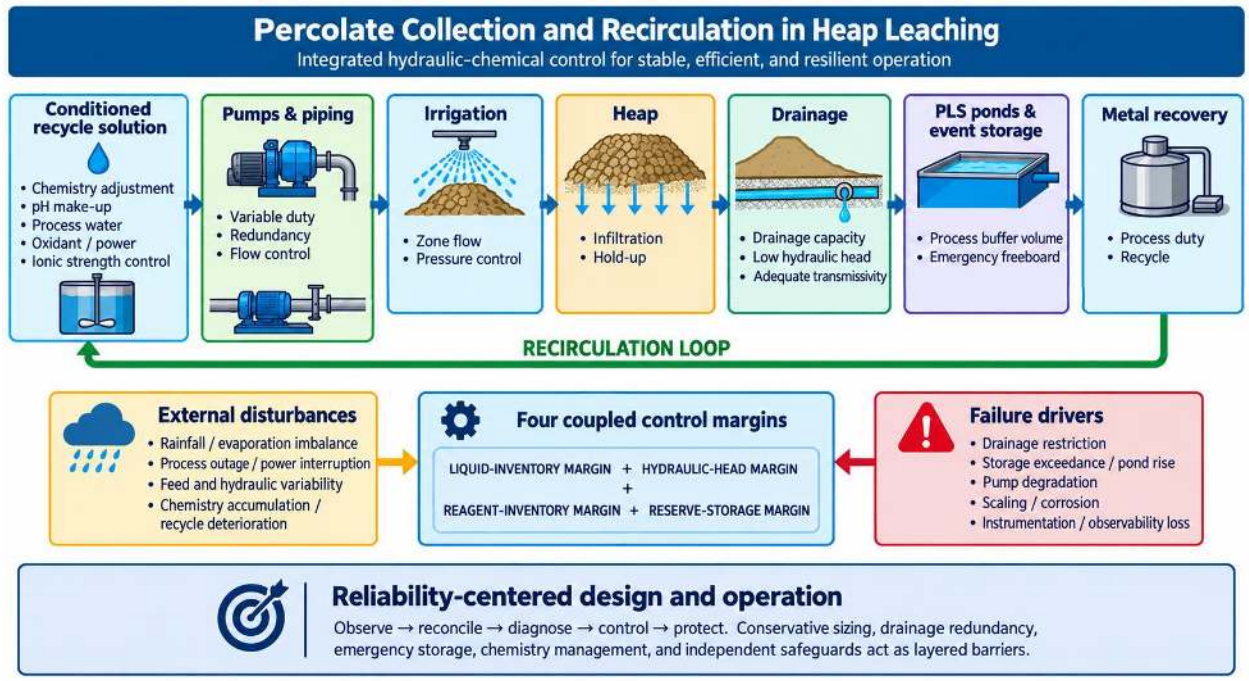
Highlights

- Collection and recirculation should be designed as core process units, not auxiliary infrastructure.
- Hydraulic head, solution inventory, reagent inventory, and storage margin must be controlled as a coupled system.
- Instrumentation and adaptive control can improve performance only when observability and physical constraints are adequate.
- Reliability is best achieved through layered barriers combining conservative sizing, redundancy, monitoring, and emergency capacity.

Graphical abstract



1. Introduction

Heap leaching derives its economic appeal from low comminution intensity and relatively simple solid handling, but the apparent simplicity masks a strongly coupled unsaturated-flow system. The underlying transport behavior is rooted in classical unsaturated porous-media theory, including Richards' formulation of capillary flow and water-retention/hydraulic-conductivity relationships used to describe saturation-dependent flow (Richards, 1931; van Genuchten, 1980).

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Irrigation initiates a transient interaction among pore structure, mineral dissolution, capillary retention, gas flow, chemical reaction, and gravity drainage. The downstream collection circuit must then accept the resulting percolate without generating excessive hydraulic head, ponding, uncontrolled saturation, erosion, leakage, or interruption of the metallurgical cycle. Consequently, recovery cannot be separated from drainage and recirculation performance: ore permeability, irrigation strategy, solution holdup, and residence-time distribution directly condition the quantity and quality of solution delivered to the ponds and returned to the heap (Robertson et al., 2022, 2023, 2024; Odidi et al., 2023a, 2023b, 2024).

The engineering literature increasingly supports this systems view. Two-dimensional hydrology models, pore-network approaches, and discrete-flow formulations demonstrate that bulk irrigation rate alone is an incomplete descriptor of solution movement because local saturation, preferential pathways, hysteresis, and pore connectivity can dominate the effective hydraulic response (Dixon & Afewu, 2022; Fernando et al., 2020; Chaitanya & Gupta, 2023; Maghsoudy et al., 2022). At the operational scale, stepwise irrigation and ramp-up procedures influence liquid holdup and consolidation, while agglomerate quality controls permeability and segregation (Wang, Yin, & Deng, 2021; Briseño Arellano et al., 2022; Yao et al., 2022; Wang, Yin, & Wu, 2021). Recent systematic reviews synthesize operational variables, reagents, and sustainability strategies in copper heap leaching (León et al., 2025), but the reliability of the collection-recirculation loop remains dispersed across hydrometallurgical, geotechnical, water-management, equipment, and control literature. These mechanisms mean that the collection and recirculation circuit is continuously exposed to flow variability rather than to the steady-state conditions often assumed in preliminary design.

Irrigation loading is best treated as a site-specific operating variable rather than as a universal design range. The total circuit duty follows from the applied flux and active area, but the acceptable operating window also depends on ore texture, lift height, climate, agglomeration, irrigation technology, hydraulic history, and metallurgical target. Water-balance work at industrial heaps and field-scale bioleaching studies reinforce that climate, solution inventory, and recycle strategy can

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become dominant constraints over a facility's life (Arpalahti & Lundström, 2020; Jia et al., 2021; Muñoz-Sepúlveda et al., 2026).

A second reason for treating recirculation as a core process function is that solution chemistry evolves during every pass. Acid is consumed by ore and gangue, dissolved salts accumulate, secondary phases may precipitate, and suspended solids or biological material can modify hydraulic resistance. Gangue acid consumption and precipitation are therefore not solely metallurgical concerns; they can alter pore geometry, pipe and emitter performance, and recycle-loop stability (Thomas, 2021; Soe et al., 2021; Ansah et al., 2025). Water reuse can further concentrate non-target constituents, creating a trade-off between freshwater efficiency and chemical and operational complexity (Miller et al., 2022; de Lima et al., 2026).

The central thesis of this review is therefore that percolate collection, equalization, chemical conditioning, pumping, and return-to-heap irrigation should be engineered as one integrated hydraulic-metallurgical control system. The review focuses on how the components interact, where conventional design assumptions fail, how monitoring can make internal states observable, and which barriers most effectively reduce the probability and consequence of loss of hydraulic control.

Terminology is used deliberately. Reliability denotes continued performance of required functions within a defined operating envelope; resilience denotes the ability to absorb disturbances and recover function; containment and safety performance concern preventing or limiting unacceptable environmental, geotechnical, or operational consequences. In this review, reliability-centered engineering means design and operation based on credible failure modes, degraded states, detection capability, independent protective layers, consequence severity, and recoverability.

2. Review Methodology and Critical Appraisal Framework

2.1 Search strategy, eligibility, and corpus consolidation

This study is a structured critical review, not a meta-analysis or PRISMA systematic review. The literature cutoff was 31 August 2026. The scoping initially identified 120 contemporary records; 96 of those records were retained for the main 2020–2026 synthesis. During revision, we

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selectively added four pre-2020 seminal sources to anchor unsaturated-flow, residence-time, and reliability theory, bringing the final bibliography to 100 references. We removed contemporary records that were redundant, nonspecific, or did not significantly inform the hydraulic-metallurgical-control-reliability framework. Database-specific hit counts and record-level exclusion codes from the initial searches were not preserved. Therefore, the 24 exclusions cannot be numerically subdivided by reason without introducing unverifiable counts, and the manuscript does not claim PRISMA record accounting.

The bibliographic framework specified Scopus, Web of Science, and Engineering Village and organized the search around three intersecting Boolean families. The first combined ("heap leach*" OR "heap leaching") with hydraulic, hydrodynamic, irrigation, infiltration, solution-holdup, saturation, and residence-time terms. The second combined ("heap leach*" OR "leach pad") with drainage, underdrain, collection, pond, liner, geomembrane, seepage, and containment terms. The third combined heap-leach or hydrometallurgical terms with raffinate, recirculation, water balance, solution chemistry, scaling, precipitation, pumping, monitoring, supervisory control and data acquisition (SCADA), state estimation, and model-predictive-control terms. We adapted database-specific syntax to the available fields and indexing conventions.

Eligibility favored peer-reviewed research and reviews published from January 2020 through August 2026 containing mechanistic, quantitative, field, monitoring, control, containment, drainage, water-balance, or reliability evidence. We included full-scale reports, permits, government guidance, and incident documentation if they provided design or operational evidence unavailable in journal articles. We interpret such sources as documented contemporary industry practice and site-specific engineering evidence, not substitutes for independently peer-reviewed causal validation. We excluded studies focused only on extraction kinetics without interpretable impact on flow, inventory, drainage, recirculation, chemistry, containment, or control. Vendor claims without traceable technical basis were not used. Pre-2020 sources were added only when indispensable for foundational theory and were not used to establish contemporary industrial performance claims.

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2.2 Evidence classification and critical appraisal

Each source was appraised using four questions: (i) which state variable or failure mechanism it shows; (ii) at what scale evidence was obtained; (iii) if it quantifies a design or operation relationship or only shows mechanistic plausibility; and (iv) how directly the finding can be applied to collection and recirculation design. This prevents pore-scale visualization, lab columns, industrial facilities, regulatory documents, and equipment analogs from being treated as equivalent evidence.

For synthesis, we grouped evidence by scale and transferability. Full-scale heap and facility evidence carried the greatest weight for design practice; pilot and column studies established transport trends and boundary-condition sensitivity; mechanistic and material-analog studies explained causal mechanisms; and modeling/control studies served as decision-support evidence, with applicability depending on calibration and observability. Table 1 makes this weighting explicit.

Table 1. Evidence classes and transferability criteria used in the critical appraisal.

Evidence class	Primary contribution	Weight for design transferability	Principal limitation
Full-scale operating heap/facility	Operating response, incidents, water balance, monitoring, reliability	Very high for practice and consequence	Site-specific geometry, ore, climate, and operating history
Pilot/demonstration	Scale-transition behavior and integrated process response	High when boundary conditions are documented	Limited duration and spatial heterogeneity
Laboratory column / packed bed	Hydrodynamics, RTD, holdup, consolidation, reaction-flow coupling	Moderate to high for mechanism	Wall effects and short drainage paths
Pore/material/component analog	Mechanisms of flow, precipitation, leakage, aging, or wear	Contextual to moderate	Indirect transfer to a full heap-leach facility

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Evidence class	Primary contribution	Weight for design transferability	Principal limitation
Technical report/permit/guideline	Industrial design basis, containment, event scenarios, operating practice	High for documented site practice	Not necessarily peer reviewed; project-specific
Model/control method	Scenario testing, state estimation, optimization, prediction	Supporting to high after validation	Model-form and parameter uncertainty
Review / secondary synthesis	Context, terminology, evidence mapping	Supporting	Depends on coverage and appraisal quality

Note. Evidence classes are weighted by directness, scale, and transferability for the design question being addressed; they are not treated as statistically equivalent observations. The appropriate evidentiary weight is question-specific: controlled experiments may be strongest for mechanism, whereas full-scale observations may be strongest for design magnitude, consequence, or operational applicability.

The hierarchy is intentionally functional rather than numerical and should not be read as a universal ranking of scientific quality. A mechanistic study can be decisive for explaining a failure pathway even when it cannot justify a design value, whereas a feasibility study or permit can document real design practice but should not be generalized beyond its site context without supporting mechanistic evidence. Project reports and permits are therefore retained as documented contemporary industry practice, explicitly distinct from peer-reviewed experimental or comparative evidence.

2.3 Synthesis logic and reproducibility limits

The synthesis used a mechanism-oriented causal-chain approach rather than vote counting: infiltration and holdup were linked to head and saturation; chemistry was linked to precipitation, solids, corrosion, and hydraulic resistance; storage and pumping were linked to upstream inventory; and monitoring and control were evaluated by their ability to detect or interrupt hypothesized causal pathways. The strength of causal inference is not assumed to be uniform across evidence classes. Controlled experiments may directly demonstrate a mechanism, whereas field reports, analog studies, and model-based control research may support plausibility,

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transferability, or engineering inference without establishing facility-wide causality. We did not attempt statistical pooling because the evidence base spans incompatible scales, commodities, climates, and response variables. The lack of preserved initial database hit counts and record-level exclusion codes is a methodological limitation, but the final manuscript reports the literature cut-off, search families, eligibility rules, retained contemporary corpus, added foundational sources, evidence classes, and appraisal questions used to produce the design-oriented synthesis.

Figure 1 summarizes the revised workflow and shows how search, eligibility, evidence classification, critical appraisal, and cross-domain synthesis lead to the reliability-centered design framework.

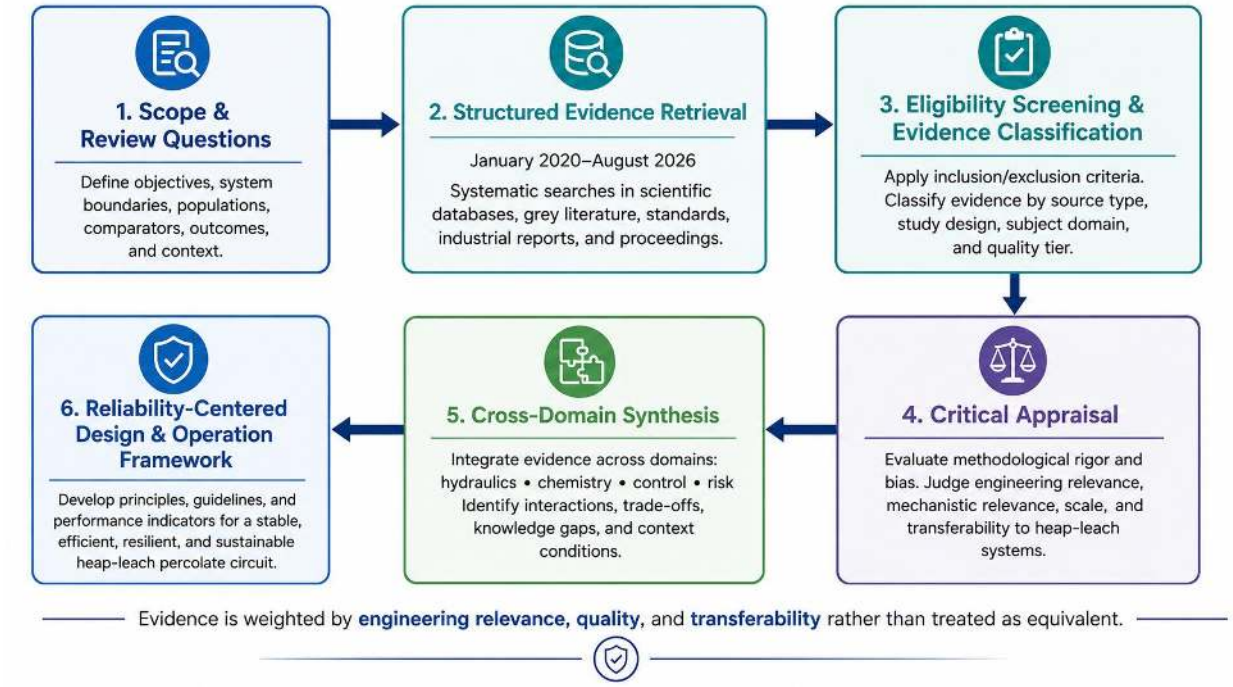

Figure 1. Structured critical-review workflow used to connect evidence, failure mechanisms, and design recommendations. Note. Original schematic developed for this review from the search, eligibility, appraisal, and synthesis procedure described in Section 2.

The workflow intentionally ends in a design framework rather than in a simple catalog of technologies. The objective is to identify mechanism-oriented pathways and transferable engineering principles: how infiltration changes internal liquid inventory; how inventory affects

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head and stability; how precipitation modifies pore and drainage geometry; how pond storage and pumping affect upstream operation; and how sensors and control strategies can interrupt adverse feedback before it propagates through the facility.

3. Integrated System Architecture, Mass Balance, and Water Inventory

3.1 Process architecture and circulating inventories

A heap-leach solution circuit can be represented by a sequence of irrigation, infiltration, reaction, drainage, collection, pond equalization, metal recovery, chemical conditioning, pumping, and re-irrigation. This sequence is cyclic rather than linear. Water, acid, dissolved metals, gangue species, heat, and suspended solids circulate at different rates, and each inventory responds to external disturbances. The practical implication is that a plant-wide mass balance must be accompanied by an inventory balance: the same total daily inflow can produce different risks depending on where solution is stored at a given time—in heap pores, drainage media, collection trenches, pipes, ponds, or tanks.

Water-balance studies demonstrate that precipitation, evaporation, ore moisture retention, solution entrainment, bleed streams, and make-up water all change the circulating inventory (Arpalahti & Lundström, 2020). At heavy-rainfall sites, operational water management must evolve over the life of the heap because geometry, exposed area, permeability, and available storage change as lifts are added (Huamanyauri et al., 2022). Environmental permits and operating documents likewise treat process ponds and event ponds as parts of a broader containment system rather than as isolated tanks (Arizona Department of Environmental Quality, 2024; Department of Water and Environmental Regulation, 2023a, 2023b).

A physically consistent inventory formulation must distinguish irreversible water loss from temporary storage. Evaporation and controlled bleed remove water from the circulating inventory, whereas solution held within pores, drainage media, pipes, or ponds represents time-dependent storage that can later reappear as drainage. Confusing loss with temporary holdup can lead to incorrect pump sizing, misleading reagent balances, or underestimated emergency storage.

$$\mathrm{d}V_{\mathrm{H}}/\mathrm{d}t = Q_{\mathrm{irr}} + Q_{\mathrm{rain,inf}} - Q_{\mathrm{drain}} - Q_{\mathrm{evap,H}} - Q_{\mathrm{other,H}}$$

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$$dV_P/dt = \sum Q_{in,P} - \sum Q_{out,P} + P\,A_P - E\,A_P$$

$$Q_{irr} = J_{irr}\,A_{active}$$

$$t_{reserve} = V_{available} / (Q_{in} - Q_{out}), \text{ for } Q_{in} > Q_{out}$$

Here, VH and VP denote heap and pond liquid inventories; Qirr and Qdrain are irrigation and drainage flows; Jirr is irrigation flux over active area Aactive; P and E are precipitation and evaporation fluxes acting over pond area AP; and treserve converts currently available storage into an instantaneous or scenario-based response-time indicator during positive net inflow. The expression assumes that Qin − Qout is approximately constant over the evaluated interval; it is not a fixed forecast. During highly transient rainfall, delayed drainage, equipment outages, or control actions, both inflow and outflow may change materially, so treserve should be recalculated dynamically. The equations are deliberately generic: individual facilities should expand the terms for runoff diversion, solution recovery, make-up, bleed, leakage surveillance, process transfers, and multiple ponds as appropriate.

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Figure 2 presents the integrated process flow considered in this review. It explicitly shows the recirculation loop, pregnant leach solution (PLS) collection, and the two dominant external disturbances—climate-driven water additions and process/ore-related solution retention.

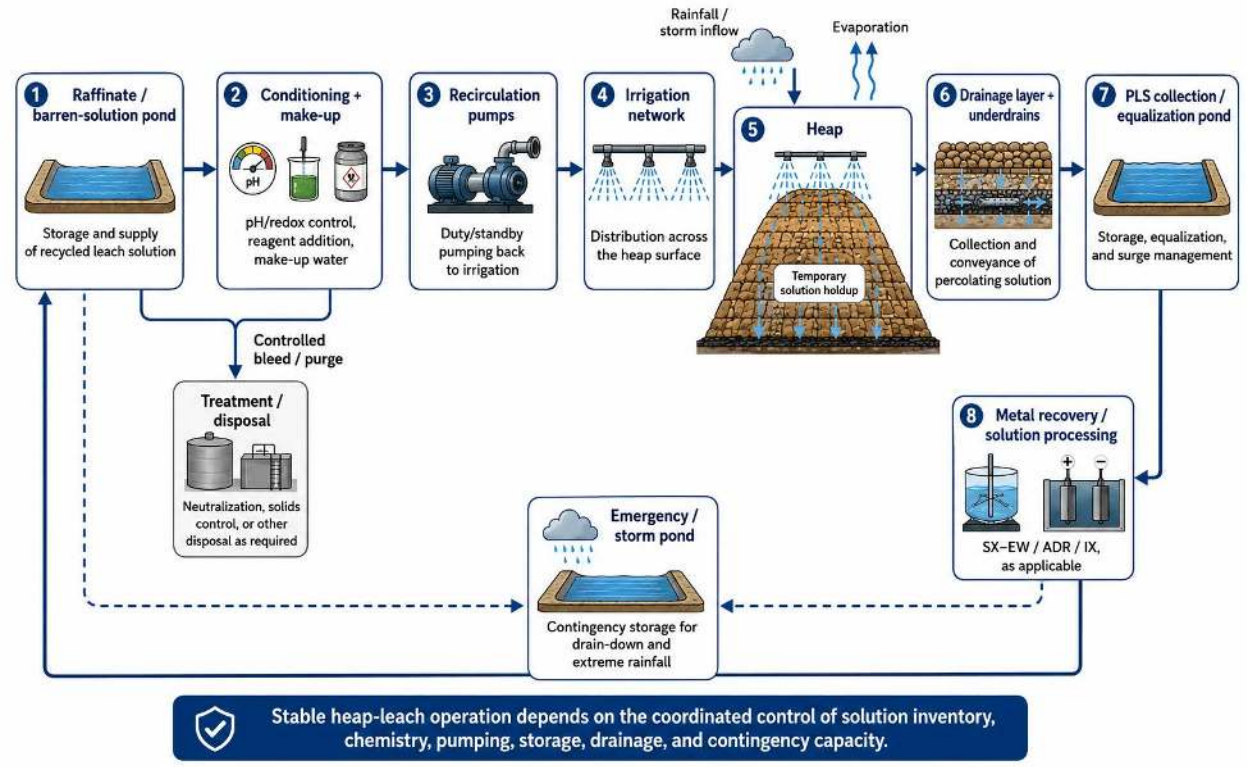

Figure 2. Integrated process flow for percolate collection, solution conditioning, and recirculation in heap leaching.
Note. Author-generated synthesis for this review using process concepts discussed by Schlesinger et al. (2021), Petersen and van Staden (2025), and Arpalahti and Lundström (2020).

3.2 Design variables and coupled constraints

The operating variables that most directly connect the heap to the collection circuit are irrigation loading, active area, infiltration acceptance, solution holdup, drainage transmissivity, pond inventory, pump operating envelope, and solution chemistry. Rather than presenting universal numerical ranges, Table 2 links each variable to the governing design basis, the evidence needed to observe it, and representative literature. This distinction is essential because full-scale

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heaps vary widely in mineralogy, lift geometry, climate, irrigation method, containment criteria, and consequence classification.

Table 2. Literature-based governing variables linking heap irrigation to collection and recirculation.

Variable	Governing design basis	Evidence/observability	Representative evidence
Irrigation loading	$Q_{irr} = J_{irr} A_{active}$; constrained by infiltration acceptance, holdup, saturation, and drainage response	Zone flow/pressure; drainage response; residence-time distribution (RTD) or moisture indicators	Robertson et al. (2022, 2023, 2024); Odidi et al. (2023a, 2023b, 2024)
Drainage-layer transmissivity	Maintain low-head transport under consolidation, fines migration, and precipitation	Sector drainage; head/saturation indicators; inspection where accessible	Ansah et al. (2025); Robertson et al. (2024); Killian (2022)
Underdrain conveyance	Local credible peak return plus delivery through drainage medium; avoid sustained pressurization	Sector flow; backwater/head indicators; cleanout condition	Killian (2022); Petersen & van Staden (2025)
Collection channels	Capacity under solids and roughness degradation without deposition, backwater, erosion, or splash	Flow/level trend; sediment and scale accumulation; inspection access	Killian (2022); contemporary project design reports
Pond operating reserve	Dynamic inflow-outflow, drainage lag, rainfall, process outage, and emergency-transfer scenarios	Level trend; usable freeboard; weather/process forecast; alternate storage	Arpalahti & Lundström (2020); Huamanyauri et al. (2022); SLR International Corporation (2024, 2025)
Pump and piping duty	System curve, TDH, NPSH, variable flow, wear/fouling, and credible equipment loss	Suction/discharge pressure; speed; flow; vibration/condition; standby availability	de Castro Pellegrini et al. (2026); de Lacerda et al. (2025); Varghese et al. (2025)

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Variable	Governing design basis	Evidence/observability	Representative evidence
Solution chemistry	Meet metallurgical target while controlling impurity accumulation, solids, scaling, and corrosion	pH plus acidity; conductivity; selected ions; suspended solids; periodic full chemistry	Thomas (2021); Soe et al. (2021); Liu et al. (2020)
Instrumentation and control	Close balances, detect divergence, and enforce independent protective limits	Redundant critical sensors; reconciliation; alarms/interlocks; internal-state sensing where justified	Daud et al. (2021); Hojat et al. (2025a, 2025b); Bárzaga-Martell et al. (2025)

Note. No universal design ranges are asserted. Numerical criteria require site-specific hydraulic characterization, dynamic water-balance scenarios, equipment calculations, containment requirements, and applicable regulatory criteria.

Table 2 shows why component-by-component design can be misleading. An irrigation loading acceptable for fresh ore may become unacceptable after consolidation or drainage blinding; a pond sized for average return can lose resilience during rainfall or downstream outage; and a pump selected at a single nominal point can move toward cavitation or inefficient operation as pond level, fouling, or irrigation zoning changes. Integrated design therefore matches transients, minimum and maximum inventories, credible degradation states, and observable operating margins rather than relying on isolated screening values.

4. Heap Drainage, Underdrain Networks, and Collection Channels

4.1 Drainage-layer function and permeability preservation

The drainage layer acts as the hydraulic interface between reactive ore and containment, intercepting percolate, distributing it to collection pipes, reducing liner hydraulic head, and protecting the liner. These functions become more demanding with higher lifts and solution inventory. The design must withstand consolidation, particle migration, mineral precipitation, and long-term chemical exposure.

Ore-side permeability is not constant. Laboratory and imaging studies show that agglomeration, pore-network structure, capillary suction, and liquid–gas competition strongly

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influence flow (Chen et al., 2020, 2021; Fernando et al., 2020; Odidi et al., 2023a). Low-permeability ores are especially sensitive to changes in saturation and flow-path continuity (Robertson et al., 2024). Mineral dissolution and precipitation can further remodel pore geometry during sulfide leaching (Ansah et al., 2025), while gangue reactions can create or consume porosity and alter local acid demand (Thomas, 2021). These mechanisms justify treating drainage transmissivity as a time-dependent reliability parameter rather than a fixed material property.

Agglomeration provides one of the principal upstream controls on drainage reliability because it limits fines migration and promotes more stable void structure. However, scale-up from laboratory agglomerates to industrial heaps remains uncertain due to segregation, curing variability, stacking damage, and lift consolidation. Reviews and mechanistic studies emphasize that binder chemistry and preparation conditions may improve initial structure but do not guarantee long-term hydraulic stability (Wang, Yin, & Wu, 2021; Pereira, 2026a). Permeability-aid concepts, such as incorporating coarse organic material, illustrate the broader principle that hydraulic architecture can be deliberately engineered, although their transferability is ore- and chemistry-specific (Yilmaz et al., 2020).

4.2 Underdrains and head control

Assess underdrain capacity against local inflow and maximum drainage response, not just average flow. Perforated pipes work best when non-pressurized and surrounded by a transmissive medium that prevents localized mounds. The goal is hydraulic-head control, not just pipe capacity, as excess head can cause leaks and geotechnical instability.

The liner system must be considered in this same chain. Research on geomembrane behavior shows that chemical environment, temperature, aging, interface condition, seam behavior, subgrade, and defect geometry all influence containment performance (Abdelaal & Rowe, 2023; Abdelaal & Solanki, 2022; Abdelaal et al., 2023; Fan & Rowe, 2023, 2024a, 2024b; Rowe & Fan, 2021, 2022). These studies are not specific to every heap-leach configuration, but they show a consistent principle: leakage consequences increase when hydraulic head persists over a defect. Drainage reliability is therefore a primary preventive barrier for liner reliability.

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Figure 3 illustrates the hydraulic relationship among heap, drainage layer, underdrains, lined collection channel, and PLS pond.

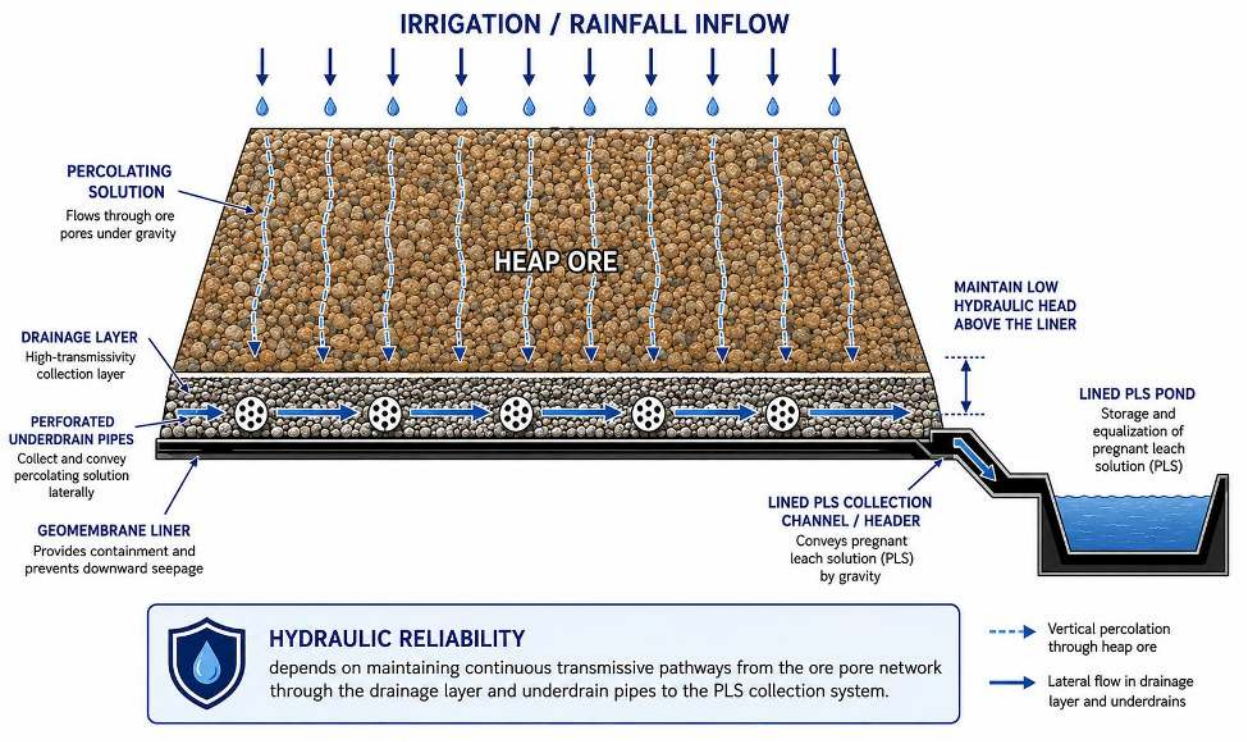

Figure 3. *Conceptual cross-section of heap drainage, underdrains, collection channel, and PLS pond.*
Note. Author-generated synthesis for this review using heap-leach drainage and containment principles discussed by Petersen and van Staden (2025), Killian (2022), and Rowe and Fan (2021, 2022).

4.3 Collection channels and solids management

Open channels and lined ditches appear simple compared with the heap itself, yet they are common operational vulnerabilities because they receive solids, scale fragments, runoff, and intermittent high flows. Hydraulic design must balance sediment transport at low velocity against erosion, splash, excessive head loss, or liner/channel damage at high velocity. The acceptable operating window depends on channel material, slope, roughness, solids characteristics, chemical exposure, and maintenance condition; a single generic velocity range is therefore not transferable across sites.

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A robust channel design includes accessible cleanout points, inspection visibility, hydraulic transitions that avoid local backwater, and allowance for progressive increases in roughness. Where precipitation or suspended fines are expected, include maintenance frequency in the hydraulic design basis. This is an important reliability distinction: a channel that only meets clean-condition capacity may have little resilience to degradation. The same principle applies to buried drains, for which inspection is difficult and preventive design is more important.

5. Pregnant Leach Solution (PLS), Raffinate, and Event Ponds: Storage, Equalization, and Containment

5.1 Ponds as hydraulic buffers

Process ponds convert a highly variable drainage signal into a manageable pumping and treatment duty. They therefore provide more than storage: they decouple short-term heap drainage from downstream process capacity, enable chemical blending, and create response time during disturbances. The critical design variable is usable buffer volume between minimum operating level and the level at which freeboard or emergency criteria are compromised.

Do not reduce operational and emergency storage to a universal day multiplier or fixed freeboard. Usable pond reserve is a site-specific result of precipitation statistics, catchment controls, heap drainage lag, downstream process downtime, pump availability, emergency-transfer capability, and regulatory or consequence-based criteria. Contemporary technical reports and permits evaluate pond capacity together with storm handling and containment rather than as an isolated average-flow volume (Asiamet Resources Limited, 2025; SLR International Corporation, 2024, 2025; Samuel Engineering, 2025; Forte Dynamics, 2026).

5.2 Dynamic pond balance and failure modes

The pond balance is fundamentally dynamic. A high-level alarm may result from rainfall, a sudden increase in heap drainage, downstream plant stoppage, reduced pump capacity, valve misalignment, or sensor error. Each cause requires a different corrective action. Simply increasing pump speed may be ineffective or unsafe if the receiving process cannot accept additional flow or

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if the suction system is approaching cavitation. Conversely, reducing irrigation to arrest pond rise may alter metallurgical kinetics and delay drainage. Effective operation therefore depends on diagnosis, not only on level control.

Table 3 organizes pond design and operation by function rather than by vessel names.

Table 3. Functional design basis for PLS, raffinate, and event ponds.

Function	Required variable	Typical control action	Key reliability question
Operational equalization	Usable volume and level trend	Modulate pump/irrigation duty	Is there enough buffer for drainage lag?
Chemical blending	pH, acidity, conductivity, metal concentration	Mixing and reagent addition	Is the pond representative and well mixed?
Surge handling	High-high level and inflow forecast	Reduce irrigation / increase transfer	Can inflow exceed transfer during transients?
Storm protection	Freeboard and event storage	Divert clean water / activate contingency storage	Are climate extremes and catchments credible?
Containment	Liner condition and leakage surveillance	Inspect, isolate, recover	How quickly can a defect be detected?
Emergency operation	Backup power, pumps, alternate storage	Transfer or shutdown in controlled sequence	What single failures defeat containment?

Note. Pond capacity should be established by dynamic water-balance scenarios rather than by a single average-flow multiplier.

The central implication of Table 3 is that storage reliability depends on both physical volume and operating discipline. A large pond run persistently near its high-level limit may be less resilient than a smaller pond maintained with adequate reserve. Freeboard is thus an operational asset that can be consumed; management systems should treat it as a monitored risk margin rather than as a fixed geometric dimension.

6. Hydraulic Control, Residence Time, Solution Holdup, and Saturation

6.1 Why flow rate alone is insufficient

A recurring weakness in heap-leach control is using irrigation rate as the principal hydraulic variable. Applied flow is easy to measure, but it does not reveal how much solution is retained, how uniformly it travels, or how quickly it reaches the drainage system. Residence-time

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distribution (RTD), a foundational non-ideal-flow concept in reaction engineering, provides a quantitative framework for interpreting transport delay and bypass (Levenspiel, 1999). Heap-leach RTD methods demonstrate that beds operating at similar nominal flow can have different transport behavior because of capillary retention, preferential flow, dead zones, and material properties (Fagan-Endres et al., 2023; Odidi et al., 2023b, 2024).

Solution holdup bridges applied irrigation and internal saturation. Stepwise irrigation experiments show hysteresis and delayed liquid release, meaning that drainage response depends on hydraulic history rather than only on the current flow rate (Wang, Yin, & Deng, 2021). Consolidation during ramp-up adds another memory effect because permeability may change as load and wetting evolve (Briseño Arellano et al., 2022; Yao et al., 2022). Consequently, a control strategy that increments irrigation solely because the current pond level is acceptable can inadvertently accumulate internal inventory until a delayed drainage or saturation response appears.

6.2 Saturation as a controlled state

Saturation zones matter for both metallurgy and stability. Excess local saturation can limit gas transfer in oxidative leaching, increase pore pressures, promote preferential bypass, and alter heat transport. Thermal monitoring has been used to infer and control saturation zones in heap-leach piles, illustrating the value of indirect state measurements when direct internal sensing is impractical (Daud et al., 2021). Electrical resistivity tomography (ERT) and borehole magnetic resonance (BMR) extend this observability toward internal PLS levels, connectivity, and moisture state (Hojat et al., 2025a, 2025b; Hosseini, 2026).

Recent control research moves beyond fixed irrigation recipes. Researchers have proposed nonlinear model-predictive control for saturation regulation, and optimal-control formulations explicitly treat infiltration conditions as decision variables (Olivares et al., 2025; Eppink & Briesen, 2026). Two-step irrigation planning methods and optimization approaches likewise recognize that spatial allocation of irrigation can improve performance when the heap is

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heterogeneous (Silva et al., 2022; Jélvez et al., 2025). These methods are promising because they target internal hydraulic states rather than simply maximizing applied flow.

6.3 Critical control logic

A practical hydraulic controller should therefore use at least three classes of information: what is being applied to the heap, what is being retained or transported internally, and what is emerging at the collection system. Applied irrigation flux and pressure represent the first class; moisture, temperature, ERT, or model-estimated saturation represent the second; and drainage flow, pond level, and solution chemistry represent the third. A persistent mismatch among these classes is diagnostic. For example, increasing applied flow without a corresponding drainage response implies rising internal inventory, leakage to an unintended pathway, or measurement error.

7. Solution Chemistry and Reagent Management in the Recirculation Loop

7.1 Reagent inventory as a chemical-hydraulic variable

Reagent management is commonly optimized around extraction and gangue consumption, but solution chemistry also affects the circuit's physical reliability. Acidity or alkalinity, ionic strength, redox conditions, and dissolved-species inventories influence mineral dissolution, secondary-phase formation, scaling tendency, corrosion, gas transfer, and the integrity of polymeric and metallic materials. In sulfuric-acid copper systems, gangue reactions can dominate acid demand and generate secondary precipitates that alter flow paths (Thomas, 2021), while jarosite precipitation in bioleaching changes iron balance and contributes solids to the circulating system (Soe et al., 2021).

Sulfuric-acid copper circuits provide a useful example of the broader control problem: acid may be corrected inline, in a pond, or in staged locations, but the appropriate setpoint is ore- and process-specific and cannot be generalized across metals or lixiviants. Other heap-leach chemistries require their own control variables and compatibility limits. The engineering question is therefore not simply where reagent is added, but how rapidly conditioned solution is mixed,

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measured, transported, and reconciled with ore demand without producing local over-conditioning, under-conditioning, precipitation, or material degradation.

7.2 Closed-loop accumulation and water reuse

Recirculation conserves water and reagent but increases the residence time of dissolved non-target species. Chloride, sulfate, iron, aluminum, magnesium, calcium, silica-related species, and organics may accumulate depending on ore and make-up water. Reuse feasibility studies in mining emphasize that water quality, treatment requirements, and process compatibility must be considered together (Miller et al., 2022; de Lima et al., 2026). In hydrometallurgical circuits, treatment technologies such as bipolar-membrane electrodialysis can treat and reuse raffinate while recovering acid functionality, although feasibility is chemistry-specific (Liu et al., 2020).

The trade-off is important: a tighter water loop can reduce freshwater demand while increasing scaling, corrosion, osmotic effects, and impurity loads. These effects may appear first in emitters, valves, pumps, and drainage pathways rather than in extraction data. A critical operating program should therefore trend conductivity, selected ions, suspended solids, and scaling indicators alongside conventional pH and metal concentrations. Where solution chemistry is scale-prone or strongly non-ideal, saturation-index calculations, aqueous-speciation modeling, and scale-potential monitoring can add an early-warning layer, provided the thermodynamic database and sampling quality match the lixiviant system.

7.3 Control strategies and limitations

Table 4 uses sulfuric-acid dosing as a specific example to compare three common conditioning locations. None is intrinsically superior; the preferred arrangement depends on mixing quality, transport delay, measurement reliability, and the consequences of dosing error.

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Table 4. Comparison of acidity-conditioning strategies in sulfuric-acid heap-leach recirculation circuits.

Strategy	Main advantage	Main limitation	Most suitable when
Inline dosing before irrigation	Fast response and direct control of feed acidity	Requires reliable flow measurement and mixing; localized dosing errors can propagate quickly	Flow is stable and instrumentation is robust
Pond-based adjustment	Provides blending volume and dampens short-term variability	Longer response; stratification may make samples unrepresentative	Pond mixing is adequate and inventory is sufficient
Split or staged dosing	Allows coarse correction plus fine trim	More instrumentation and control complexity	Chemistry varies materially through the cycle

Note. In sulfuric-acid circuits, control should consider free or titratable acidity and process response in addition to pH when buffering, ionic strength, or dissolved salts are significant. Other lixiviants require chemistry-specific control variables.

The limitation of pH-only control deserves emphasis. In strongly acidic systems, pH may change little even when free-acid inventory changes materially, and dissolved salts can affect electrode response. For process control, acidity titration, conductivity, density, and periodic full-solution analysis may therefore be needed to validate the online pH. The risk of overcontrol is equally important: aggressive acid addition can increase consumption, accelerate material degradation, or dissolve additional gangue without improving valuable-metal recovery.

8. Recirculation Pumps, Piping, and Return-to-Heap Irrigation

8.1 Pump selection as a variable-duty problem

Recirculation pumps operate at the boundary between inventory control and irrigation performance. Their duty changes with pond level, active irrigation area, pipe configuration, solution density, fouling, and wear. Pump sizing therefore cannot be represented by a universal flow or head range: selection should be based on the site system curve, total dynamic head (TDH), net positive suction head (NPSH) margin, expected zoning, minimum-flow requirements, and credible degraded states or train outages.

Pump reliability studies in mining emphasize abrasion, fatigue, transient operation, and maintenance. Fracture analysis of slurry-pump shafts shows how mechanical degradation can arise

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from combined material and loading conditions, while broader reviews identify energy efficiency, wear, and proactive maintenance as central sustainability concerns (de Lacerda et al., 2025; Varghese et al., 2025; Werbinska-Wojciechowska & Rogowski, 2025; Wróbel et al., 2025). This slurry-pump literature is used here only as analog evidence for general wear, fatigue, and reliability mechanisms; it is not used to quantify degradation rates for heap-leach solution pumps, whose solids loading, rheology, chemistry, and duty may differ substantially. Heap-leach recycle service can nevertheless face suspended fines, precipitates, and corrosive chemistry that activate related reliability mechanisms.

Pump selection should therefore be evaluated across an operating envelope rather than at one design point. Recent energy-based selection frameworks for centrifugal pumps under slow transients are relevant because recirculation systems frequently move between irrigation zones and pond levels (de Castro Pellegrini et al., 2026). Variable-speed drives can improve control efficiency, but only if they respect minimum flow, suction conditions, and hydraulic stability.

8.2 Cavitation, air ingress, and solids

Cavitation risk increases when pond level falls, suction losses rise, solution temperature changes, or gas is entrained. A control system that accelerates a pump to maintain irrigation flow during low pond level can therefore create a damaging positive feedback: lower level reduces available suction head, increased speed raises demand, and cavitation further reduces effective capacity. Low-level interlocks, suction-pressure monitoring, and pump-curve validation are thus part of hydraulic reliability rather than merely equipment protection.

Solids management is similarly coupled. Fine particles can abrade pumps, deposit in low-velocity pipe sections, block emitters, or accumulate in ponds. Where precipitation products form, include periodic flushing, accessible cleanouts, and velocity management in the design. The objective is not to eliminate solids—often impossible—but to control where they accumulate so that maintenance occurs in accessible components rather than in buried drains or irrigation emitters.

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8.3 Return-to-heap distribution

The return line completes the control loop by converting pump output into spatial irrigation. Uniformity depends on network pressure, emitter condition, topographic elevation, valve position, and zoning. Surface moisture mapping using drone imagery and convolutional neural networks demonstrates that irrigation distribution can be assessed remotely at operational scale (Tang & Esmaeili, 2021), while hyperspectral mapping provides a broader example of remote sensing applied to heap characterization (He et al., 2022). These tools support a shift from assuming uniformity of distribution to measuring it.

The most reliable design therefore treats the irrigation network as an actuator with known limitations. Monitor pressure and flow by zone, not only at the pump discharge. Total flow matching the target does not guarantee spatially correct application; clogged emitters in one area can be masked by excessive flow elsewhere. This distinction is essential when control strategies optimize irrigation plans or saturation states.

9. Instrumentation, Monitoring, Data Reconciliation, and Advanced Control

9.1 Core and enhanced observability architecture

A collection and recirculation system cannot be controlled more precisely than it is observed. Core observability should cover variables that are broadly necessary for safe routine operation: irrigation flow and pressure by zone, drainage flow, pond levels, pump suction/discharge conditions, and essential solution chemistry. pH, oxidation-reduction potential, conductivity, temperature, and density are common online candidates, while periodic laboratory analyses provide calibration and impurity tracking. Enhanced observability is site-specific and may include thermal imaging, ERT, BMR, interferometric synthetic aperture radar (InSAR), other remote sensing, and state estimators. Justify enhanced tools by consequence, uncertainty, and decision value rather than treating them as universal requirements.

Monitoring technologies are advancing rapidly, but their maturity should be stated explicitly. Thermal monitoring and drone-based surface-moisture mapping have field-demonstration

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evidence (Daud et al., 2021; Tang & Esmaeili, 2021). ERT includes both field case-study and synthetic-survey-design evidence (Hojat et al., 2025a, 2025b), while BMR has recent in-situ field demonstration for raffinate flow and pore-connectivity monitoring (Hosseini, 2026). InSAR is operationally established for deformation monitoring in geotechnical practice, but its use for forecasting heap-leach failure remains an active and developing application (Bar et al., 2025; Szakolczai et al., 2026). For this review, advanced technologies are classified conceptually as full-scale operational, field demonstration, pilot, simulation/model validation, or emerging concept; no technology is promoted beyond the maturity supported by its cited evidence.

9.2 State estimation and digital control

Recent work on heap-leach control includes deep reinforcement learning, Kalman-filter state estimation, hybrid phenomenological–neural models, and digital twins (Canales et al., 2024; Bárzaga-Martell et al., 2025; Bravo-Gutiérrez et al., 2026; Tarrés-Puertas et al., 2026). These methods are attractive because many critical states—internal moisture, acid consumption, and distributed saturation—are not directly measurable. State estimation can combine imperfect sensors with mechanistic constraints to infer these hidden variables. Their maturity, however, is heterogeneous: Kalman-filter and hybrid-model studies primarily provide model/data validation; reinforcement-learning, model-predictive-control, and digital-twin studies remain predominantly simulation-, model-, or prototype-based in this evidence set. They should not be interpreted as proof of established full-scale reliability benefit.

However, the control literature should not be interpreted as evidence that more advanced algorithms automatically improve industrial reliability. A controller trained on a model inherits model bias; a soft sensor inherits drift from its input instruments; and optimization can drive the system toward an unsafe region if constraints are incomplete. The most robust architecture uses analytics to augment, not replace, physical safeguards. High-high pond level, minimum pump suction, maximum irrigation pressure, and emergency shutdown logic should remain independently enforceable.

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Figure 4 shows the revised, simplified layered control architecture: core and enhanced sensing feed validation and reconciliation, state estimation and constrained control, and finally actuation through pumps, valves, dosing, and irrigation zoning, while independent safeguards remain separately enforceable.

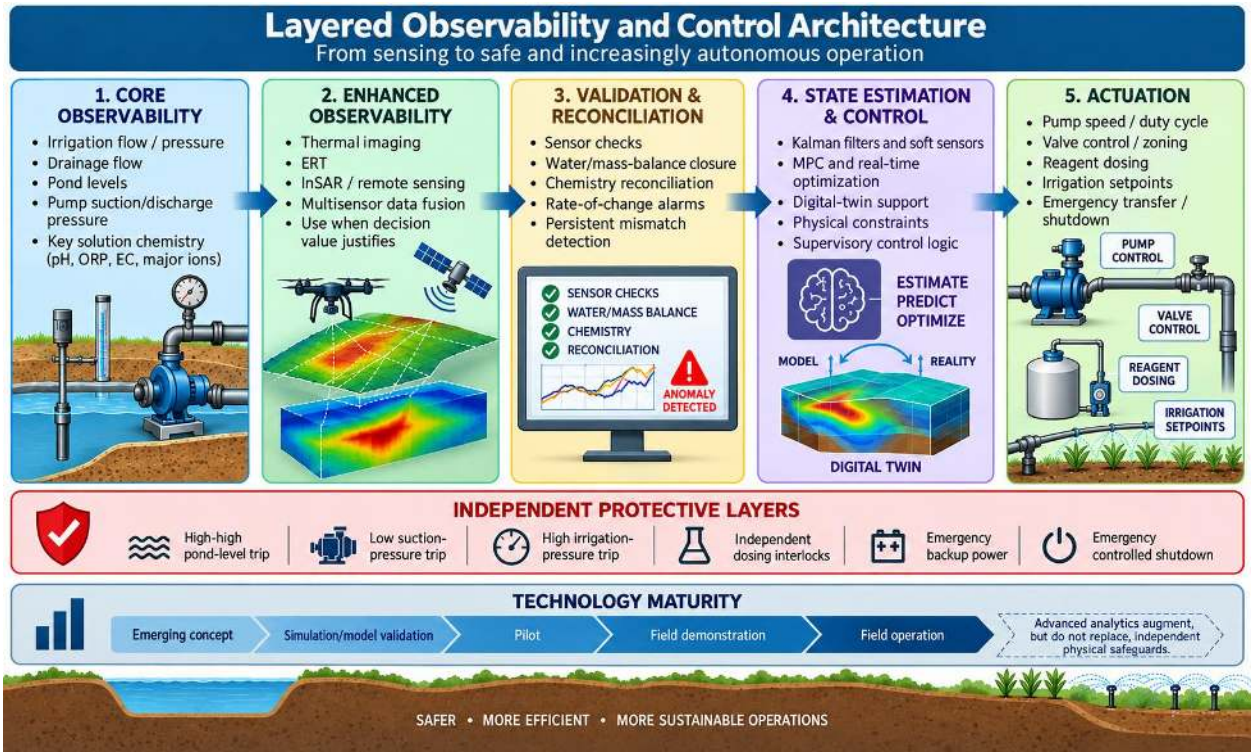

Figure 4. Layered instrumentation and control architecture for heap-leach collection and recirculation.
Note. Author-generated synthesis for this review. The simplified architecture distinguishes core from enhanced observability and separates field-demonstrated sensing from model- or simulation-based control concepts reported by Daud et al. (2021), Canales et al. (2024), Bárzaga-Martell et al. (2025), Olivares et al. (2025), and Eppink and Briesen (2026).

9.3 Data reconciliation and alarm quality

Data reconciliation is an underdeveloped but practical requirement. Flow meters, pond level, and estimated heap inventory should approximately close the water balance over appropriate time windows. Persistent imbalance signals sensor drift, unmeasured rainfall or evaporation, leakage, unexpected holdup, or operating-data errors. Similarly, acid added should reconcile with solution acidity changes, ore consumption, and bleed streams at a process-relevant timescale.

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Alarm design should distinguish between rate of change and absolute thresholds. A pond level still within normal range but rising rapidly during a storm may require earlier intervention than a higher but stable level. Conversely, frequent nuisance alarms reduce operator trust. Reliability therefore depends on alarm rationalization, sensor validation, and defined response actions—not just on installing additional transmitters.

10. Environmental, Geotechnical, and Operational Risk Integration

10.1 Hydraulic control as a geotechnical barrier

Hydraulic and geotechnical performance are tightly coupled because solution inventory affects saturation and pore-pressure conditions. Three-dimensional seepage and slope-stability assessments, observational monitoring methods, and failure-mechanism studies all show that water distribution and drainage cannot be separated from stability evaluation (Dompierre et al., 2023; Grass et al., 2022; Bar & Zlobin, 2025; Pourverdi et al., 2025). In dynamic-heap facilities, geometry and loading change with stacking, so the hydraulic system must remain effective throughout construction and operation, not only in the final design configuration.

The 2024 Eagle Gold heap-leach failure intensified attention to integrating design, operations, monitoring, and emergency response. Independent and operational documentation around the facility illustrates how heap-leach risk extends beyond metallurgical performance to major environmental and geotechnical consequences (Smith & Konrad, 2025; Smith & Sinha, 2022a, 2022b; Victoria Gold (Yukon) Corp., 2020; Victoria Gold Corp., 2024). This case illustrates interacting failure pathways and system-level consequences, not a single causal mechanism or universal hydraulic design criteria.

10.2 Containment and leakage

Geomembrane performance must be evaluated against chemical aging, puncture, seams, interfaces, and sustained head. Long-term studies show that polymer degradation under extreme chemical conditions is not negligible, while experimental leakage studies show leakage rate sensitivity to defect geometry and subgrade conditions (e Silva et al., 2025; Abdelaal & Samea,

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2023; Clinton & Rowe, 2025; Rowe & Fan, 2021, 2022). The implication for recirculation design is direct: maintaining low head over the liner reduces the hydraulic driving force for leakage and provides a first line of defense even when defects cannot be entirely eliminated.

10.3 Extreme rainfall, water scarcity, and climate resilience

Heap-leach water management must be resilient to both excess and scarcity. Heavy rainfall can rapidly consume pond freeboard and increase internal heap inventory, whereas drought and high evaporation increase make-up water demand and concentrate dissolved salts. Industrial water-balance work and water-reuse studies show that the correct objective is not minimum freshwater use in isolation, but a stable process-water system that remains chemically and hydraulically manageable (Arpalahti & Lundström, 2020; Huamanyauri et al., 2022; Miller et al., 2022; de Lima et al., 2026).

Facility guidelines and environmental assessments now often demand scenario-based water management and consequence-informed design (Government of Yukon, 2023; Bureau of Land Management, 2025; Romero et al., 2025). For collection and recirculation systems, climate resilience includes maintaining reserve storage, drainage, backup transfer, and procedures for rainfall sequences, not just designing for a single nominal storm.

10.4 Failure modes and barriers

Table 5 summarizes representative failure modes and shows that preventive barriers often differ from mitigating barriers. This distinction matters because redundancy should target the dominant failure chain rather than merely duplicating equipment.

Table 5. Representative failure modes in percolate collection and recirculation systems.

Failure mode	Initiating causes	Potential consequences	Preventive / mitigating barriers
Drainage restriction	Fines migration, precipitation, collapse, low transmissivity	Rising head, saturation, leakage, instability	Agglomeration control; drainage margin; cleanouts; saturation monitoring

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Failure mode	Initiating causes	Potential consequences	Preventive / mitigating barriers
Pond high-high level	Storm inflow, plant outage, pump loss, delayed drainage	Overtopping, forced shutdown, environmental release	Event storage; independent high-level alarm; backup transfer; irrigation reduction
Pump loss of capacity	Wear, cavitation, power loss, blockage	Pond rise, loss of irrigation, unstable chemistry	Duty/standby trains; Variable-frequency drive (VFD) limits; condition monitoring; backup power
Acid-control deviation	Sensor drift, dosing fault, poor mixing	Low extraction, overconsumption, corrosion, precipitation	Independent checks; acidity titration; dosing interlocks; staged correction
Irrigation maldistribution	Emitter blockage, pressure imbalance, valve error	Dry zones, channeling, local saturation	Zone flow/pressure monitoring; flushing; aerial moisture checks
Containment defect	Puncture, seam degradation, aging, settlement	Seepage and environmental impact	Low head; leak detection; inspection; secondary containment where required
Loss of observability	Sensor failure, bad calibration, communications loss	Delayed diagnosis and inappropriate control action	Redundant critical sensors; reconciliation; fail-safe control states

Note. Failure modes are synthesized from the hydraulic, containment, pump-reliability, monitoring, and incident literature cited in Sections 4–10.

The table highlights a central design principle: hydraulic reliability is layered. No single instrument, pond, pump, or liner should be expected to prevent all outcomes. Instead, design margin reduces the probability of events, monitoring shortens detection time, automation improves response speed, redundant capacity sustains function after equipment failure, and emergency storage limits the consequences when normal control is lost.

11. Scale-Up, Design Uncertainty, and Reliability-Centered Engineering

11.1 Why laboratory hydraulic success does not guarantee heap performance

Scale-up is especially difficult in heap leaching because the hydraulic geometry changes qualitatively with scale. Laboratory columns can characterize kinetic and transport tendencies, but industrial heaps introduce lift-scale segregation, stacking damage, spatially variable compaction,

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long lateral drainage distances, climate exposure, and operational zoning. Fundamentally based scale-up work emphasizes the need to preserve relevant physical mechanisms rather than simply extrapolate extraction curves (van Staden & Petersen, 2021). Critical reviews of column testing similarly caution that boundary conditions and wall effects can produce hydraulic artifacts that do not represent industrial heaps (Pereira, 2026b, 2026c, 2026d).

As a result, collection design should account for increased transient variability as the system scales. A laboratory column may drain through a short, well-defined path, whereas a hectare-scale irrigation zone contains many flow paths with different residence times. Field permeability evaluation and blending studies are therefore important complements to metallurgical extraction tests (Keller et al., 2022).

11.2 Modeling as a design aid, not a substitute for monitoring

Numerical models can represent seepage, reaction, heat, and transport at increasing levels of complexity. HeapSim2D, reactive-flow models, bioleaching simulations, and machine-learning approaches demonstrate substantial progress (Dixon & Afewu, 2022; Wang et al., 2024; González et al., 2026; Nie et al., 2026; Saldaña, Gálvez, et al., 2022; Saldaña, Neira, et al., 2022; Saldaña et al., 2023). Models are especially valuable for testing scenarios that are impractical or unsafe to create intentionally, such as high rainfall, pump outage, or progressive drainage restriction.

Nevertheless, design decisions should account for model uncertainty. Hydraulic parameters are spatially variable and can evolve over time; reaction networks may be incompletely characterized; and operational disturbances may not match assumed distributions. The best use of models is therefore iterative: initial design establishes conservative capacity; commissioning data calibrate parameters; monitoring detects deviation; and the model is updated to support operating decisions. This is closer to a digital twin than to a one-time design calculation.

11.3 Reliability-centered design margins

Reliability-centered engineering, as used here, means designing and operating the circuit around credible failure modes, degraded states, detection capability, independent protective layers, consequence severity, and recoverability (Rausand & Høyland, 2004). For recirculation systems,

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useful scenarios include one pump unavailable, one flow meter biased, one drainage sector partially blocked, one pond liner under repair, one storm coincident with downstream plant outage, and one irrigation zone receiving excess flow. The system should be tested against credible combinations, not only single independent failures.

Consequence classification approaches for heap-leach pads provide a rationale for scaling design and monitoring conservatism to the potential failure outcome (Romero et al., 2025). Where consequences are high, low-probability combinations deserve explicit treatment. The framework also supports lifecycle decisions: as pumps wear, liners age, or drainage performance changes, the operating envelope can be reduced to preserve reliability rather than continue using the original nominal limits.

12. Critical Synthesis, Best-Practice Framework, and Research Priorities

12.1 Where conventional designs fail conceptually

The literature reviewed here suggests five recurring conceptual failures. First, steady-state design is applied to a system whose defining behavior is transient. Second, total irrigation flow is treated as a proxy for internal hydraulic condition even though holdup and saturation can vary independently. Third, drainage, ponds, pumps, and irrigation are designed in separate packages without explicitly reconciling inventories and control response. Fourth, chemical control is optimized for metallurgy without sufficient consideration of scaling, solids, corrosion, and accumulation in recycle streams. Fifth, instrumentation is added after design rather than being treated as the architecture that makes operating risk observable.

These failures can produce both underdesign and overdesign. Undersized drainage or ponds obviously increase risk, but overdesign is not automatically benign. Oversized pumps operating far from their efficient range can increase energy use and cavitation risk; oversized ponds with poor mixing can increase chemical residence time and stratification; and excessively conservative irrigation can unnecessarily suppress recovery. The objective is not maximum capacity but a controlled operating envelope with sufficient margin against credible disturbances.

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12.2 Integrated best-practice framework

Table 6 presents a practical framework. It organizes design and operation around coupled state variables rather than around equipment lists.

Table 6. Integrated best-practice framework for collection and recirculation.

Layer	Design objective	Minimum evidence/instrumentation	Decision criterion
Heap hydraulic state	Keep saturation and holdup within a validated envelope	Irrigation by zone; drainage response; moisture/thermal/geophysical indicators where needed	No persistent divergence between applied and recovered flow
Drainage/underdrain	Maintain low head and transmissivity under degradation	Drain flow by sector; inspection/cleanout strategy	Capacity demonstrated for transient and degraded states
Ponds	Preserve operational and emergency buffer	Independent level measurement; inflow/outflow trending; freeboard tracking	Defined reserve margin under credible event scenarios
Chemistry	Maintain extraction-effective solution without uncontrolled accumulation	pH plus acidity and periodic full chemistry; solids/scaling tracking	Stable reagent inventory and no progressive impurity-driven degradation
Pumps/piping	Deliver required duty with one credible failure	Duty/standby logic; suction/discharge pressure; condition monitoring	Operating point remains inside safe hydraulic envelope
Irrigation return	Deliver spatially correct flow and pressure	Zone flow/pressure; emitter checks; surface distribution monitoring	Target uniformity achieved without local saturation
Control/alarms	Detect imbalance early and enforce safe response	Reconciled water balance; alarm rationalization; interlocks	Independent protective layers remain effective during analytics failure
Emergency response	Limit consequence when normal control is lost	Alternate storage/transfer; backup power; shutdown sequence	Response time shorter than time to loss of containment

Note. The framework synthesizes the reviewed evidence on hydraulics, monitoring, containment, pumps, and controls and is intended to be adapted to site-specific consequence criteria.

The most important shift in Table 6 is from fixed design values to observable operating margins. For example, pond freeboard is tracked as the remaining response time; pump capacity is considered alongside suction conditions and standby availability; and irrigation targets are

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constrained by drainage response. These are operationally meaningful quantities because they support decisions before absolute limits are exceeded.

12.3 Research priorities

Several research gaps remain. The first is long-duration quantification of permeability and drainage degradation under realistic recycle chemistry. Many studies characterize flow or mineral reaction over laboratory timescales, while industrial heaps operate for months to years. Coupled datasets linking precipitation, solids migration, pore-structure evolution, and drainage performance would improve reliability forecasting. A particularly high priority is creating anonymized multi-site industrial datasets covering underdrain degradation, pond operating reserve, recirculation-pump reliability histories, drainage blockage, and long-term chemistry accumulation so cross-site reliability claims can be tested rather than inferred from isolated projects.

The second gap is scale-aware validation of internal-state sensing. ERT, thermal imaging, remote sensing, and magnetic resonance methods are promising, but their decision value depends on spatial resolution, calibration stability, and interpretability under varying mineralogy and solution chemistry. Research should compare these technologies using common field events—such as irrigation step changes, known wet zones, or controlled shutdowns—rather than evaluating them solely as isolated sensing demonstrations.

The third gap is integration of hydraulic reliability into techno-economic optimization. Most optimization frameworks focus on extraction, reagent consumption, or irrigation scheduling. Future work should include the expected cost of failures, emergency storage, pump redundancy, maintenance, and environmental consequences. This would discourage economically attractive operating points that rely on narrow hydraulic margins.

The fourth gap is adaptive management of water and chemistry under climate variability. Studies of water scarcity and heavy rainfall are often treated separately, but both affect the same circulating inventory. Closed-loop control that uses weather forecasts, pond capacity, heap holdup estimates, and solution chemistry could create a unified resilience framework.

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12.4 Limitations of the evidence base

The evidence base is uneven across the integrated circuit. Heap hydrodynamics and laboratory transport are comparatively well represented, whereas detailed full-scale information on drainage-network degradation, pond operating margins, recirculation-pump duty, and maintenance history is often embedded in proprietary engineering records rather than peer-reviewed publications. Consequently, convergent mechanisms and project practice support several design implications rather than controlled cross-site comparisons.

A second limitation is heterogeneous transferability across commodities and lixiviants. Evidence from copper acid leaching, gold cyanidation, bioleaching, geomembrane testing, slurry-pump services, and general mining-water management is not equally direct. The appraisal framework therefore uses analog evidence only to explain mechanisms or reliability principles and avoids treating it as a universal numerical design basis. Climate, ore texture, lift geometry, solution chemistry, and consequence classification remain site-specific modifiers.

Finally, the initial database hit counts and record-level exclusion codes were not preserved during iterative corpus development. The review is therefore best interpreted as a transparent, structured critical review of 96 retained contemporary records supplemented by four selectively added seminal references, not as a claim of exhaustive capture by systematic review. Future updates would benefit from prospectively registered search strings and database-level screening logs.

Figure 5 condenses the review into a qualitative bow-tie reliability synthesis in which initiating threats pass through preventive barriers before the top event, while mitigating barriers act between loss of hydraulic control and its consequences. The framework does not assign event

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probabilities and is not a substitute for site-specific FMEA, HAZOP, quantified bow-tie analysis, or geotechnical risk assessment.

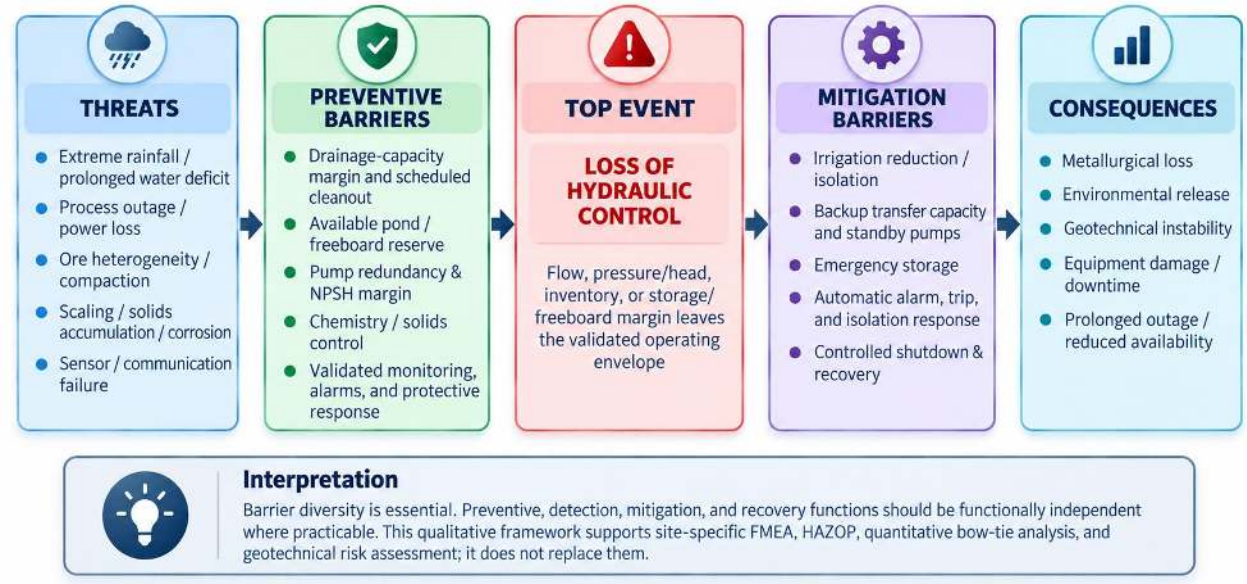

Figure 5. Reliability framework for preventing and mitigating loss of hydraulic control in heap-leach solution circuits.
Note. Author-generated qualitative synthesis for this review using risk-control concepts discussed by Bar and Zlobin (2025), Romero et al. (2025), and Smith and Sinha (2022a, 2022b). The schematic does not assign event probabilities or replace site-specific quantitative risk assessment.

The reliability framework emphasizes that control comes from diverse barriers. A high-level pond alarm does not prevent a blocked drain; a standby pump does not detect poor irrigation distribution; and a liner does not eliminate the consequence of prolonged hydraulic head. Reliability concerns continued function, resilience concerns absorption and recovery, and containment/safety performance concerns limitation of unacceptable consequences; the framework keeps these functions related but distinct.

13. Conclusions

Percolate collection and recirculation systems govern much more than the transport of solution around a heap-leach circuit. They determine how quickly the heap can release solution, how much liquid is retained internally, how effectively reagent inventory is controlled, how much storage margin remains during disturbances, and how strongly hydraulic conditions load the containment

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and geotechnical systems. For this reason, drainage, ponds, pumps, chemical conditioning, irrigation return, and monitoring should be designed as one coupled process system.

The central engineering requirement is to control four interacting quantities simultaneously: liquid inventory, hydraulic head, reagent inventory, and reserve storage. Maximizing flow, minimizing freshwater use, or tightening a reagent strength or chemistry target independently can shift risk elsewhere in the system. A reliable design therefore uses conservative but not indiscriminate capacity margins, protects drainage transmissivity, maintains pump redundancy and safe suction conditions, preserves pond freeboard, and verifies solution chemistry beyond a single pH measurement.

The strongest pathway for future improvement is adaptive operation supported by better observability. Internal saturation sensing, remote monitoring, state estimation, and model-based control can help operators identify developing imbalances before they appear in ponds or recovery data. Their value, however, depends on validated physical constraints and independent protective layers. Digital methods should strengthen engineering barriers, not substitute for them.

A reliability-centered approach ultimately reframes collection and recirculation from auxiliary infrastructure into the hydraulic backbone of heap leaching. The framework is broadly transferable across commodities and lixiviants at the level of principles—inventory control, head control, observability, barrier diversity, degraded-state analysis, and recoverability—but numerical design criteria are not universally transferable and must remain site-specific. When treated this way, the circuit becomes an explicit lever for metallurgical recovery, reagent efficiency, water resilience, environmental protection, and facility-wide risk reduction.

Declarations

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Conflict of Interest
The author declares no conflict of interest.

Data Availability
No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

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References

Abdelaal, F. B., & Rowe, R. K. (2023). Physical and mechanical performance of an HDPE geomembrane in 10 mining solutions with different pHs. Canadian Geotechnical Journal, 60(7), 978–993. https://doi.org/10.1139/cgj-2022-0419

Abdelaal, F. B., Rowe, R. K., Morsy, M. S., & e Silva, R. A. (2023). Degradation of HDPE, LLDPE, and blended polyethylene geomembranes in extremely low and high pH mining solutions at 85 °C. Geotextiles and Geomembranes, 51(5), 27–38. https://doi.org/10.1016/j.geotexmem.2023.04.011

Abdelaal, F. B., & Samea, A. (2023). Chemical durability of bituminous geomembranes (BGMs) in heap leach pad applications. Geosynthetics International, 31(5), 506–523. https://doi.org/10.1680/jgein.22.00333

Abdelaal, F. B., & Solanki, R. (2022). Effect of geotextile ageing and geomembrane surface roughness on the geomembrane–geotextile interfaces for heap leaching applications. Geotextiles and Geomembranes, 50(1), 55–68. https://doi.org/10.1016/j.geotexmem.2021.09.001

Ansah, E. O., Black, J. R., & Haese, R. R. (2025). Impact of mineral dissolution–precipitation on pore geometry during copper sulphide heap leaching. Minerals Engineering, 230, 109379. https://doi.org/10.1016/j.mineng.2025.109379

Arizona Department of Environmental Quality. (2024). Individual Aquifer Protection Permit No. P-513690: Copper World, Inc. https://static.azdeq.gov/permits/copperworld/wqd_app_2024permit.pdf

Arpalahti, A., & Lundström, M. (2020). Water balance of a boreal black schist heap leach operation. Mine Water and the Environment, 39(4), 758–768. https://doi.org/10.1007/s10230-020-00694-7

Asiamet Resources Limited. (2025). BKM Project feasibility study 2025: Executive summary. https://asiametresources.com/wp-content/uploads/2025/05/BKM-Feasibility-Study-2025-Executive-Summary.pdf

Bar, N., McQuillan, A., Zlobin, G., & Meloni, F. (2025). Criticality of 3D numerical modeling for assessing heap leach pad stability and integration with monitoring data, including InSAR. In Proceedings of Heap Leach Solutions 2025. https://scholarwolf.unr.edu/items/75bbdc4c-3530-427b-88a2-10454189dbd5

Bar, N., & Zlobin, G. A. (2025). The geotechnical analysis in the design and risk control at heap leaching pads. Gornyi Zhurnal, (1). https://doi.org/10.17580/gzh.2025.01.16

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Bárzaga-Martell, L., Díaz-Quezada, S., Estay, H., & Ruiz-del-Solar, J. (2025). Estimation of copper grade, acid consumption, and moisture content in heap leaching using extended and unscented Kalman filters. Minerals, 15(5), 521. https://doi.org/10.3390/min15050521

Bravo-Gutiérrez, M., Henríquez-Vargas, L., Díaz-Quezada, S., & Estay, H. (2026). Towards generalized heap leaching modeling: A hybrid approach of phenomenological-principles and neural networks. Minerals Engineering, 242, 110197. https://doi.org/10.1016/j.mineng.2026.110197

Briseño Arellano, A. D., Yao, T.-M., Milczarek, M., & Brusseau, M. L. (2022). Column experiments to assess consolidation behaviour at different initial irrigation rates in copper heap leaching. In Proceedings of Heap Leach Solutions 2022 (pp. 259–271). https://www.heapleachsolutions.ca/2022-proceedings/

Bureau of Land Management. (2025). Spring Valley Mine Project: Final environmental impact statement. https://cdxapps.epa.gov/cdx-enepa-II/public/action/eis/details?eisId=517667

Canales, C., Díaz-Quezada, S., Leiva, F., Estay, H., & Ruiz-del-Solar, J. (2024). Control of heap leach piles using deep reinforcement learning. Minerals Engineering, 212, 108707. https://doi.org/10.1016/j.mineng.2024.108707

Chaitanya, G. V. A., & Gupta, G. S. (2023). Liquid flow in heap leaching using the discrete liquid flow model and graph-based void search algorithm. Hydrometallurgy, 221, 106151. https://doi.org/10.1016/j.hydromet.2023.106151

Chen, K., Yin, W., Ma, Y., Yang, B., Sun, H., Rao, F., & Liu, J. (2021). Microstructure analysis of low-grade copper ore agglomerates prepared by geopolymerization. Hydrometallurgy, 200, 105564. https://doi.org/10.1016/j.hydromet.2021.105564

Chen, K., Yin, W., Rao, F., Wu, J., Zhu, Z., & Tang, Y. (2020). Agglomeration of fine-sized copper ore in heap leaching through geopolymerization process. Minerals Engineering, 159, 106649. https://doi.org/10.1016/j.mineng.2020.106649

Clinton, M., & Rowe, R. K. (2025). Effect of underliner on the strain and puncture response of a bituminous geomembrane in heap leach applications. Canadian Geotechnical Journal, 62, 1–19. https://doi.org/10.1139/cgj-2025-0055

Daud, O., Correa, M., Estay, H., & Ruiz-del-Solar, J. (2021). Monitoring and controlling saturation zones in heap leach piles using thermal analysis. Minerals, 11(2), 115. https://doi.org/10.3390/min11020115

de Castro Pellegrini, C., da Silva, M. L. F., Pedrera-Yanes, J., Llanes-Santiago, O., & Vilalta-Alonso, G. (2026). An energy-based framework for selecting centrifugal pumps under slow transient operation. Energy Conversion and Management, 365, 121807. https://doi.org/10.1016/j.enconman.2026.121807

de Lacerda, J. C., Teixeira, R. L. P., dos Reis, W. D., Garcia, A. S. T., de Brito, T. G., & Brito, R. F. (2025). Fracture analysis of a centrifugal ore slurry pump shaft: A study using fatigue tests, microstructural analysis and finite element simulation. Multiscale and Multidisciplinary

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Modeling, Experiments and Design, 8, Article 83. https://doi.org/10.1007/s41939-024-00675-1

de Lima, J. P. M., de Lima, S. C. R. B., & Amaral, M. C. S. (2026). Integrated framework assessment of water reuse feasibility in mining. Environmental Geochemistry and Health, 48, Article 383. https://doi.org/10.1007/s10653-026-03244-2

Department of Water and Environmental Regulation. (2023a). Licence L9362/2022/1: Norton Gold Fields Pty Ltd—Binduli Operations. Government of Western Australia. https://der.wa.gov.au/component/k2/item/24541-l9362-2022-1

Department of Water and Environmental Regulation. (2023b). Works approval amendment report W6504/2021/1: Norton Gold Fields Pty Ltd. Government of Western Australia. https://www.der.wa.gov.au/our-work/licences-and-works-approvals/lwa-applications/item/23013-w6504-2021-1

Dixon, D. G., & Afewu, K. I. (2022). HeapSim2D: A two-dimensional model of heap leach hydrology. Minerals Engineering, 183, 107555. https://doi.org/10.1016/j.mineng.2022.107555

Dompierre, K., Castonguay, V., & Kelln, C. (2023). 3D seepage and slope stability assessment of a heap leach pad. In Proceedings of the 76th Canadian Geotechnical Conference (GeoSaskatoon, 2023). Canadian Geotechnical Society. https://www.cgsconferences.ca/en/GEO2023/GEO2023_110.html

e Silva, R. A., Abdelaal, F. B., & Rowe, R. K. (2025). A 9-year study of the degradation of a HDPE geomembrane liner used in different high pH mining applications. Geotextiles and Geomembranes, 53(1), 230–246. https://doi.org/10.1016/j.geotexmem.2024.09.012

Eppink, A., & Briesen, H. (2026). Optimal control of infiltration conditions in heap leaching. Minerals Engineering, 236, 109945. https://doi.org/10.1016/j.mineng.2025.109945

Fagan-Endres, M. A., Odidi, M. D., & Harrison, S. T. L. (2023). An accurate residence time distribution measurement method for low volumetric flowrate systems, with application to heap leaching columns. Chemical Engineering Communications, 210(11), 2057–2063. https://doi.org/10.1080/00986445.2023.2169679

Fan, J., & Rowe, R. K. (2023). Effect of subgrade on leakage through a defective geomembrane seam below saturated tailings. Geotextiles and Geomembranes, 51(2), 360–369. https://doi.org/10.1016/j.geotexmem.2022.12.003

Fan, J., & Rowe, R. K. (2024a). Creep rupture behaviour of elastomeric bituminous geomembrane seams. Geotextiles and Geomembranes, 52(6), 1134–1144. https://doi.org/10.1016/j.geotexmem.2024.07.003

Fan, J., & Rowe, R. K. (2024b). Effect of a lateral drainage layer on leakage through a defect in a geomembrane overlain by saturated tailings. Geotextiles and Geomembranes, 52(4), 383–395. https://doi.org/10.1016/j.geotexmem.2023.12.004

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Fernando, W. A. M., Ilankoon, I. M. S. K., Rabbani, A., & Chong, M. N. (2020). Applicability of pore networks to evaluate the inter-particle flow in heap leaching. Hydrometallurgy, 197, 105451. https://doi.org/10.1016/j.hydromet.2020.105451

Forte Dynamics, LLC. (2026). Feasibility study and technical report on the DeLamar Project, Owyhee County, Idaho, USA. Prepared for Integra Resources Corp. https://www.sec.gov/Archives/edgar/data/1722387/000106299326000533/exhibit99-1.htm

González, B., Díaz-Quezada, S., Bravo-Gutiérrez, M., Muñoz-Sepúlveda, A., Montserrat, S., Hernández, P., Liu, W., Vargas, T., & Estay, H. (2026). Modeling and simulation of copper sulfide chloride-based heap leaching. Hydrometallurgy, 243, 106722. https://doi.org/10.1016/j.hydromet.2026.106722

Government of Yukon. (2023). Guidelines for mine waste management facilities. https://yukon.ca/en/guidelines-mine-waste-management-facilities

Grass, M., Nketia, P., & Jester, C. (2022). Geotechnical engineering: The observational method applied to monitoring of slopes during operational activities for heap leach pad facilities. In Proceedings of Heap Leach Solutions 2022. https://www.heapleachsolutions.ca/WPwebsite/wp-content/uploads/2024/10/12.-Geotechnical-Engineering-The-Observational-Method.pdf

He, J., DuPlessis, L., & Barton, I. (2022). Heap leach pad mapping with drone-based hyperspectral remote sensing at the Safford Copper Mine, Arizona. Hydrometallurgy, 211, 105872. https://doi.org/10.1016/j.hydromet.2022.105872

Hojat, A., Karimi-Nasab, S., Mohammadi Vizheh, M., Mohamadrezaei, H., Loke, M. H., & Zanzi, L. (2025a). ERT surveys to detect PLS levels in heap leaching pads: Sarcheshmeh Copper Mine case study. In Proceedings of NSG 2025: 6th Conference on Geophysics for Mineral Exploration and Mining. https://doi.org/10.3997/2214-4609.202520009

Hojat, A., Karimi-Nasab, S., Mohammadi Vizheh, M., Mohamadrezaei, H., Loke, M. H., & Zanzi, L. (2025b). Synthetic simulations to design ERT surveys for detecting PLS levels in Sarcheshmeh Heap Leaching No. 2. In Proceedings of NSG 2025: 6th Conference on Geophysics for Mineral Exploration and Mining. https://doi.org/10.3997/2214-4609.202520010

Hosseini, M. (2026). In-situ monitoring of raffinate flow and pore connectivity evolution in heap leach waste rock using borehole magnetic resonance. Hydrometallurgy, 244, 106806. https://doi.org/10.1016/j.hydromet.2026.106806

Huamanyauri, J., Villanueva, C., Mamani, M., & Pacheco, A. (2022). Changes in water management during heap leach lifetime in heavy-rainfall sites. In Proceedings of Heap Leach Solutions 2022 (pp. 161–168). https://anddes.com/wp-content/uploads/2025/08/Changes-in-water-management-during-heap-leach-lifetime-in-heavy-rainfall-sites.pdf

Jélvez, E., de Sousa e Silva, J., Díaz-Quezada, S., Morales, N., Vargas, T., & Estay, H. (2025). A novel methodology to generate an optimal irrigation plan on a copper-oxide ore heap leaching process. Minerals Engineering, 233, 109660. https://doi.org/10.1016/j.mineng.2025.109660

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Jia, Y., Sun, H., Tan, Q., Xu, J., Feng, X., & Ruan, R. (2021). Industrial heap bioleaching of copper sulfide ore started with only water irrigation. Minerals, 11(11), 1299. https://doi.org/10.3390/min11111299

Keller, J., Yao, T.-M., Milczarek, M., Lofftus, V., & Myrhow, S. (2022). Ore permeability and blending evaluation to optimize leach performance. In Proceedings of Heap Leach Solutions 2022 (pp. 79–89). https://www.gsanalysis.com/publications/Keller-et-al-2022-Ore-Permeability-and-Blending-Evaluation-to-Optimize-Leach-Performance.pdf

Killian, J. (2022). Lone Star leach pad design, construction and operation. In Proceedings of Heap Leach Solutions 2022 (pp. 39–48). https://www.heapleachsolutions.ca/2022-proceedings/

León, F., Rojas, L., Bazán, V., Martínez, Y., Peña, A., & Garcia, J. (2025). A systematic review of copper heap leaching: Key operational variables, green reagents, and sustainable engineering strategies. Processes, 13(5), 1513. https://doi.org/10.3390/pr13051513

Levenspiel, O. (1999). Chemical reaction engineering (3rd ed.). John Wiley & Sons.

Liu, Y., Zhang, T., Wang, Y., & Chen, Y. (2020). Raffinate treatment and reuse by bipolar membrane electrodialysis for copper hydrometallurgical circuits. Chemical Engineering Journal, 382, 122956. https://doi.org/10.1016/j.cej.2019.122956

Maghsoudy, S., Bakhtiari, O., & Maghsoudy, S. (2022). Tortuosity prediction and investigation of fluid flow behavior using pore flow approach in heap leaching. Hydrometallurgy, 211, 105868. https://doi.org/10.1016/j.hydromet.2022.105868

Miller, K. D., Bentley, M. J., Ryan, J. N., Linden, K. G., Larison, C., Kienzle, B. A., Katz, L. E., Wilson, A. M., Cox, J. T., Kurup, P., Van Allsburg, K. M., McCall, J., Macknick, J. E., Talmadge, M. S., Miara, A., Sitterley, K. A., Evans, A., Thirumaran, K., Malhotra, M., … Chellam, S. (2022). Mine water use, treatment, and reuse in the United States: A look at current industry practices and select case studies. ACS ES&T Engineering, 2(3), 391–408. https://doi.org/10.1021/acsestengg.1c00244

Muñoz-Sepúlveda, A., Vargas, T., Díaz-Quezada, S., Niño, Y., Estay, H., & Montserrat, S. (2026). Heap bioleaching of copper sulfide ores: Integrated numerical assessment of environmental influences at industrial scale. Hydrometallurgy, 244, 106763. https://doi.org/10.1016/j.hydromet.2026.106763

Nie, R., Yang, X., Tian, B., Li, W., Liu, X., Wen, J., & Yang, H. (2026). Review of numerical simulations for parameter control in heap bioleaching of copper sulfide ore. Minerals, 16(6), 568. https://doi.org/10.3390/min16060568

Odidi, M. D., Fagan-Endres, M. A., & Harrison, S. T. L. (2023a). Moisture absorption rates via capillary suction within packed beds—The effect of material and fluid properties with implications for heap leaching operations. Hydrometallurgy, 215, 105975. https://doi.org/10.1016/j.hydromet.2022.105975

Odidi, M. D., Fagan-Endres, M. A., & Harrison, S. T. L. (2023b). Residence time distribution analysis of drip-irrigated beds—The effect of material and fluid properties with implications for heap leaching practice. Minerals, 13(2), 267. https://doi.org/10.3390/min13020267

CC BY

JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Odidi, M. D., Fagan-Endres, M. A., & Harrison, S. T. L. (2024). Comparison of nonreactive solute transport models to evaluate fluid flow in packed beds, with implications for heap leaching practice. Hydrometallurgy, 230, 106395. https://doi.org/10.1016/j.hydromet.2024.106395

Olivares, B., Araya, B., Quintanilla, P., & Navia, D. (2025). Saturation regulation in heap leaching: A nonlinear model predictive control approach. Minerals Engineering, 229, 109346. https://doi.org/10.1016/j.mineng.2025.109346

Pereira, A. C. (2026a). Agglomeration of fine ores for heap leaching: Mechanisms, design parameters, and scale-up limitations. IKR Journal of Engineering and Technology, 2(3), 1–20. https://doi.org/10.5281/zenodo.20046848

Pereira, A. C. (2026b). Do tall columns truly represent industrial heaps? A critical review of nickel heap leach testwork. International Journal of Current Science Research and Review, 9(5), 2267–2301. https://doi.org/10.47191/ijcsrr/V9-i5-05

Pereira, A. C. (2026c). From columns to industrial heaps: Critical design considerations for heap leach pilot plants. International Journal of Modern Research in Engineering and Technology, 11(3), 1–41. https://doi.org/10.5281/zenodo.18979542

Pereira, A. C. (2026d). Short column tests for nickel heap leaching: Critical review of test design, hydraulic artifacts, and scale-up reliability. REMUNOM, 13(7), 1–58. https://doi.org/10.66104/y9zx6g57

Petersen, J., & van Staden, P. J. (2025). Heap leaching: Process, principles, and practical considerations. In Treatise on Process Metallurgy (Vol. 2B, pp. 333–345). Elsevier. https://doi.org/10.1016/B978-0-443-40294-4.00029-3

Pourverdi, A., Doulati Ardejani, F., Maghsoudy, S., Kafi, R., & Taherdangkoo, R. (2025). Coupled hydro-mechanical analysis and stabilization of a failing heap leaching structure. Bulletin of Engineering Geology and the Environment, 84(11), 476. https://doi.org/10.1007/s10064-025-04487-6

Rausand, M., & Høyland, A. (2004). System reliability theory: Models, statistical methods, and applications (2nd ed.). John Wiley & Sons. https://doi.org/10.1002/9780470316900

Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. Physics, 1(5), 318–333. https://doi.org/10.1063/1.1745010

Robertson, S. W., Basson, P., Brill, S., van Staden, P. J., & Petersen, J. (2024). Properties governing the flow of solution through crushed ore for heap leaching: Part III—Low-permeability ores. Hydrometallurgy, 224, 106247. https://doi.org/10.1016/j.hydromet.2023.106247

Robertson, S. W., Basson, P., van Staden, P. J., & Petersen, J. (2023). Properties governing flow of solution and air through crushed ore for heap leaching: Part II—Unsaturated dual-phase flow. Hydrometallurgy, 215, 105990. https://doi.org/10.1016/j.hydromet.2022.105990

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Robertson, S. W., van Staden, P. J., Cherkaev, A., & Petersen, J. (2022). Properties governing the flow of solution through crushed ore for heap leaching. Hydrometallurgy, 208, 105811. https://doi.org/10.1016/j.hydromet.2021.105811

Romero, F. M. S., Negron, J., Parra, D., & Valdivia, R. (2025). Consequence classification approach for heap leach pad design. In Proceedings of Heap Leach Solutions 2025. https://scholarwolf.unr.edu/items/0eee7281-51ef-45c2-900c-3700b74f849a

Rowe, R. K., & Fan, J. (2021). Effect of geomembrane hole geometry on leakage overlain by saturated tailings. Geotextiles and Geomembranes, 49(6), 1506–1518. https://doi.org/10.1016/j.geotexmem.2021.06.004

Rowe, R. K., & Fan, J. (2022). A general solution for leakage through geomembrane defects overlain by saturated tailings and underlain by highly permeable subgrade. Geotextiles and Geomembranes, 50(4), 694–707. https://doi.org/10.1016/j.geotexmem.2022.03.010

Saldaña, M., Gálvez, E., Robles, P., Castillo, J., & Toro, N. (2022). Copper mineral leaching mathematical models—A review. Materials, 15(5), 1757. https://doi.org/10.3390/ma15051757

Saldaña, M., Jeldres, M., Galleguillos Madrid, F. M., Gallegos, S., Salazar, I., Robles, P., & Toro, N. (2023). Bioleaching modeling—A review. Materials, 16(10), 3812. https://doi.org/10.3390/ma16103812

Saldaña, M., Neira, P., Gallegos, S., Salinas-Rodríguez, E., Pérez-Rey, I., & Toro, N. (2022). Mineral leaching modeling through machine learning algorithms—A review. Frontiers in Earth Science, 10, 816751. https://doi.org/10.3389/feart.2022.816751

Samuel Engineering, Inc. (2025). 2025 feasibility study NI 43-101 technical report on the regenerative Los Azules Copper Mining Project. Prepared for McEwen Copper Inc. https://s21.q4cdn.com/390685383/files/technical_reports/los_azules/McEwen_NI43-101_TR_Los_Azules_Nov_2025.pdf

Schlesinger, M. E., Sole, K. C., Davenport, W. G., & Alvear Flores, G. R. F. (2021). Extractive metallurgy of copper (6th ed.). Elsevier. https://doi.org/10.1016/C2019-0-03265-7

Silva, J., Díaz-Quezada, S., Espinoza, J. P., Contreras, I., Morales, N., Vargas, T., Estay, H., & Jélvez, E. (2022). A two-step methodology to generate an optimal irrigation plan for heap leaching operations. In Copper 2022. Santiago, Chile. https://copper2022.cl/wp-content/uploads/2022/04/Compilado_Abstracts_Hydrometallurgy.pdf

SLR International Corporation. (2024). Technical report summary on the Marigold Complex, Nevada, USA (SLR Project No. 138.21581.00002). Prepared for SSR Mining Inc. https://www.sec.gov/Archives/edgar/data/921638/000094787124000126/ss2975198_ex9602.htm

SLR International Corporation. (2025). Review of the 2024 Coffee Project heap leach facility design report (SLR Project No. 123.020532.00001). Prepared for GoldCorp Kaminak Ltd. https://emr-ftp.gov.yk.ca/emrweb/COMM/major-mines/coffee-gold/emr-2024-coffee-project-review.pdf

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Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Smith, M. E., & Konrad, J.-M. (2025). Eagle Gold Mine: June 2024 heap leach failure, Yukon, Canada—Independent Review Board report. https://www.pwc.com/ca/en/services/insolvency-assignments/victoriagold/independent-review-board-report.html

Smith, M. E., & Sinha, K. P. (2022a). Eagle Gold heap leach facility and cyanide management review (Project 4667). Piteau Associates Engineering Ltd. https://emrlibrary.gov.yk.ca/minerals/MajorMines/eaglegold/eagle-gold-heap-leach-facility-and-cyanide-management-review-2022.pdf

Smith, M. E., & Sinha, K. P. (2022b). Liquefaction in heap leach piles—A primer. In Proceedings of Heap Leach Solutions 2022. https://www.heapleachsolutions.ca/2022-proceedings/

Soe, K. M., Ruan, R., Jia, Y., Tan, Q., Wang, Z., Shi, J., Zhong, C., & Sun, H. (2021). Influence of jarosite precipitation on iron balance in heap bioleaching at Monywa copper mine. Journal of Mining Institute, 247, 102–113. https://doi.org/10.31897/PMI.2020.1.11

Szakolczai, S., Piciullo, L., Frauenfelder, R., Vöge, M., Carlà, T., & Intrieri, E. (2026). Forecasting the time of failure of tailings dams and heap leach facilities through satellite InSAR data: Myth or reality? Remote Sensing Applications: Society and Environment, 42, 101963. https://doi.org/10.1016/j.rsase.2026.101963

Tang, M., & Esmaeili, K. (2021). Heap leach pad surface moisture monitoring using drone-based aerial images and convolutional neural networks: A case study at the El Gallo Mine, Mexico. Remote Sensing, 13(8), 1420. https://doi.org/10.3390/rs13081420

Tarrés-Puertas, M. I., Vives-Pons, J., & Dorado, A. D. (2026). ML-driven Unity/WebGL digital twin with RGB sensing for bioleaching process control. IEEE Transactions on Industrial Informatics, 22(7), 6535–6545. https://doi.org/10.1109/TII.2026.3679379

Thomas, M. J. (2021). Understanding gangue acid consumption in copper sulfide heap leaching: Predicting the impact of carbonates, silicates and secondary precipitates. Minerals Engineering, 171, 107090. https://doi.org/10.1016/j.mineng.2021.107090

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

van Staden, P. J., & Petersen, J. (2021). Fundamentally based heap leach scale-up. Minerals Engineering, 168, 106915. https://doi.org/10.1016/j.mineng.2021.106915

Varghese, A., Martins, S., Lessing, E., Hassan, G. M., & Karrech, A. (2025). A systematic review on the sustainability of slurry pumps in the mining industry. Minerals Engineering, 234, 109731. https://doi.org/10.1016/j.mineng.2025.109731

Victoria Gold Corp. (2024). Heap leach process facilities emergency response plan (Version 2024-01). https://emr-ftp.gov.yk.ca/emrweb/COMM/major-mines/eagle-gold/

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JIRRS
Journal International Review of Research Studies

Received: 12/08/2026 - **Accepted:** 17/09/2026
Vol: 01.09
DOI: 10.66104/4p6d0h27
Pages: 1-44

Victoria Gold (Yukon) Corp. (2020). Eagle Gold Project: Heap leach facility operation, maintenance and surveillance manual (Version 2020-01). https://yukon.ca/en/science-and-natural-resources/mining/eagle-gold-project-licensing-documents

Wang, L., Cheng, L., Zhang, X., Yin, S., Zhang, X., Li, H., Luo, Y., & Zhang, L. (2024). Reactive fluid flow (RFF), its hydrodynamic modeling and process controlling in cleaner production of copper sulfides bioleaching. Journal of Cleaner Production, 441, 140792. https://doi.org/10.1016/j.jclepro.2024.140792

Wang, L., Yin, S., & Deng, B. (2021). Understanding the effect of stepwise irrigation on liquid holdup and hysteresis behavior of unsaturated ore heap. Minerals, 11(11), 1180. https://doi.org/10.3390/min11111180

Wang, L., Yin, S., & Wu, A. (2021). Ore agglomeration behavior and its key controlling factors in heap leaching of low-grade copper minerals. Journal of Cleaner Production, 279, 123705. https://doi.org/10.1016/j.jclepro.2020.123705

Werbinska-Wojciechowska, S., & Rogowski, R. (2025). Proactive maintenance of pump systems operating in the mining industry—A systematic review. Sensors, 25(8), 2365. https://doi.org/10.3390/s25082365

Wróbel, J., Pietrusiak, D., Rozmus, R., Roicki, R., Zarzycki, B., & Stefanek, P. (2025). Failure analysis and guidelines for further exploitation of centrifugal slurry pumps used for copper flotation waste transport: A case study. Engineering Failure Analysis, 174, 109479. https://doi.org/10.1016/j.engfailanal.2025.109479

Yao, T.-M., Milczarek, M., Briseño Arellano, A. D., & Brusseau, M. L. (2022). Laboratory and numerical approach to assess ore consolidation and solution distribution during ramp-up. In Proceedings of Heap Leach Solutions 2022 (pp. 207–220). https://www.heapleachsolutions.ca/2022-proceedings/

Yilmaz, S., Sirkeci, A. A., Bilen, M., & Kizgut, S. (2020). Increasing the heap leach efficiency of Uşak Kışladağ gold ore using nut shell as permeability aid. Hydrometallurgy, 198, 105520. https://doi.org/10.1016/j.hydromet.2020.105520

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