Modelling river systems under change – Quantifying climate driven risks to environmental values in complex regional systems

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Key points

- Traditional deterministic methods for modelling river systems can underrepresent climate risk and uncertainty in complex river systems.
- A bottom-up stochastic modelling framework, or system stress testing, can expose system vulnerabilities to different climate driven shifts, such as natural variability, climate change, changing water demands, and the sequencing of wet and dry periods.
- This approach represents a methodological shift from a projection of future events to exploring system vulnerabilities across a range of plausible changes.
- The application to the Latrobe River system demonstrates how this approach provides deeper insights into environmental flow impacts under changing climate conditions.

Abstract

Modelling river systems under change can create deep uncertainty in representing dynamic water demands, climate variability and climate change. This is particularly challenging in mine rehabilitation, where large local hydrologic changes can propagate downstream and interact with vulnerable water-dependent environmental values. Yet common practice in water balance modelling for mine closure and Environmental Impact Assessments typically applies a small number of fixed demand assumptions and climate scenarios, using uniform scaling of historical flows. This can obscure how ecologically relevant flow components change through time and limit assessment of whether environmental values remain within acceptable thresholds under plausible futures. Nor does it allow insight to be drawn from multiple dimensions of change, such as different manifestations of climate change, or the relationship between reduction in rainfall and shift in seasonality.

This paper presents a bottom-up stochastic modelling framework developed to support threshold-based assessment of environmental values under deep uncertainty. The framework couples dynamic water demands that change over time and respond to climate with stochastic climate sequences to represent natural variability. Climate change is represented as a range of plausible rainfall and temperature end states applied progressively through time, rather than as static adjustments. Large ensembles of simulations are run stochastically using a Source river system model to quantify the distribution of outcomes and the likelihood of environmental performance thresholds at critical flow compliance locations being exceeded.

Using the Yallourn mine rehabilitation project in Victoria's Latrobe Valley, we show how the framework improves attribution of risk to climate versus operational decisions, supports comparison of alternative rehabilitation and water management strategies, and provides a transparent, updateable basis for stress-testing environmental flow tolerance under uncertain futures.

Keywords

Hydrologic modelling, water balance modelling, climate change, environmental risk assessment, bottom-up system stress testing

Introduction

Climate change is increasingly posing significant challenges to water systems and river systems, particularly through altered rainfall patterns, rising temperatures, and changing streamflow regimes

(Douville et al., 2021). Regional river systems affected by large-scale development, land-use change, urban expansion or mine rehabilitation present an additional layer of complexity for understanding whether environmental objectives can be achieved and sustained (Younger & Wolkersdorfer, 2004). It also involves understanding how altered local hydrologic conditions can propagate downstream, affecting urban and rural consumptive uses, environmental water provisions, and compliance requirements, all within operating constraints embedded in entitlement frameworks and water sharing rules (Poff et al., 2010). These interacting pressures make mine closure planning increasingly uncertain and multi-dimensional.

Hydrological modelling is therefore essential under these complex and interacting conditions. A key challenge in this setting arises from the combined effects of hydroclimatic variability, climate change, and evolving water demands (Fowler et al., 2024). Historical variability in rainfall, temperature, and streamflow already generates substantial interannual and decadal fluctuations in water availability, which directly affect environmental flow compliance and system performance (Poff et al., 2010; Palmer et al., 2008). This is compounded by uncertainty in future climate change, including the magnitude, timing, and direction of change, as well as how these changes propagate through different components of the flow regime (Poff et al., 2010; Peterson et al., 2021). At the same time, closure-related water demands are dynamic, often peaking during early rehabilitation activities such as pit filling, while broader external demands may also shift due to climate, policy, and infrastructure changes. This results in a coupled system where both supply and demand evolve over time, and outcomes are highly sensitive to the sequencing of wet and dry periods.

Conventional mine-closure water-balance assessments often evaluate a limited number of defined climate and operational scenarios, with future climate conditions represented by applying adjustment factors derived from climate projections to historical rainfall and evaporation records (Clarke, 2025). This can obscure how ecologically relevant flow components change through time and limit understanding of whether environmental flow recommendations remain robust under a range of plausible futures (Arthington et al., 2006). It also restricts insight into how different aspects of climate change, such as shifts in seasonality or changes in rainfall magnitude, interact to affect flow regimes.

This paper presents a bottom-up stochastic modelling framework designed to support stress testing of environmental flow recommendations. The framework couples dynamic water demands that evolve over time with stochastic climate sequences that represent natural variability, while climate change is represented as a range of time varying signals applied to rainfall to represent plausible long-term trends in increases or reductions of rainfall. Large ensembles of simulations are undertaken using a Source river system model to explore how environmental flow thresholds perform under a wide range of hydroclimatic conditions. The framework is demonstrated using the Yallourn mine rehabilitation project in Victoria's Latrobe Valley, showing how it enables deeper insight into how environmental flow recommendations behave under complex and uncertain futures, and how performance is influenced by both climate variability and operational decisions.

Environmental flow analysis in complex regional systems

Environmental flow recommendations define the flow conditions required to sustain key ecological and geomorphic processes in regulated river systems (Arthington et al., 2006). A key difficulty is that environmental flow recommendations are typically expressed as performance criteria tied to specific components of the flow regime, such as low flows, freshes, and high-flow events (DEECA, 2024). These components are sensitive not only to total water availability, but also to timing, sequencing, and variability of flows.

In mine closure contexts, these recommendations become embedded within long-term operational rules governing pit lake levels, managed releases, and downstream flow management, effectively linking ecological objectives to engineered hydrological systems (REFS). In addition, mine closure systems further introduce additional storage, evaporation losses, and managed release rules, which can reshape the natural flow regime in ways that are not easily predictable from inflow conditions alone. As a result, the relationship between climate, operational decisions, and ecological flow outcomes becomes indirect and highly dependent on system design and management choices.

The shift away from deterministic methods

Hydrological and water balance assessments for mine closure have traditionally relied on deterministic modelling approaches. In these applications, a model is typically run using a defined climate sequence, a selected set of demand assumptions, and a limited number of climate change scenarios (Fraser et al., 2011). The resulting outputs are then interpreted to infer likely system behaviour, environmental flow impacts, and potential risks to downstream users and environmental values. This approach has been valuable for establishing baseline conditions, comparing defined development options, and demonstrating compliance under agreed assumptions. However, its usefulness becomes more limited where the system is exposed to multiple interacting sources of uncertainty.

A key limitation of using deterministic modelling in mine closure settings is that it provides only a small sample of a broad range of plausible outcomes (Brown et al., 2012). Even where several scenarios are assessed, each simulation represents one selected combination of climate, demand, operating rules, and system configuration. The outputs therefore describe what occurs under those assumptions, rather than how the system responds across the broader range of plausible future conditions. This distinction is important in complex regional water systems, where outcomes may be strongly influenced by the sequencing of wet and dry periods, the timing of rehabilitation water demands, changing climate conditions, and operational rules governing storage, diversions, and releases. In these settings, a single modelled sequence may provide a plausible outcome, but it does not provide a statistical basis for understanding the likelihood, persistence, or thresholds of environmental flow impacts.

This limitation is particularly important for environmental flow assessment. Environmental flow recommendations are often expressed through flow components and compliance metrics that depend on timing, seasonality, event frequency, and antecedent conditions. A deterministic simulation may indicate whether a particular environmental flow target is achieved under one scenario, but it does not reveal how close the system is to failure, which combinations of conditions lead to non-compliance, or whether performance is robust across plausible futures. As a result, decision-making depends heavily on expert interpretation of model outputs, including assumptions about how representative the selected scenario is, how much confidence should be placed in the simulated sequence, and how far the modelled outcome may deviate from future reality.

Bottom-up stress testing changes the role of modelling in this process. Rather than beginning with a small number of predefined futures and asking what outcome they produce, the approach begins with the decision problem and tests the system across a wide range of plausible conditions. In this framing, modelling is used to identify how the system behaves as climate, demand, and operating conditions vary, and to locate the thresholds at which environmental objectives are met, degraded, or no longer achieved. The emphasis therefore shifts from prediction to response: the model is not used only to produce a single output for interpretation, but to map the range of system behaviour that is relevant to the decision.

This provides a stronger basis for decision-making under deep uncertainty. By generating ensembles of model outcomes, bottom-up methods allow environmental flow performance to be expressed as distributions, likelihoods, response surfaces, and threshold exceedance metrics. These outputs provide direct insight into the conditions under which a system is vulnerable and the conditions under which management options remain robust. For mine rehabilitation, this is particularly valuable because closure decisions may alter water demands, storage behaviour, downstream flow regimes, and environmental outcomes over long timeframes. A bottom-up framework can therefore help distinguish risks associated with natural hydroclimatic variability, climate change trajectories, and operational or design choices.

The shift away from deterministic methods does not mean that deterministic models no longer have value. Deterministic modelling remains important for representing system processes, testing agreed scenarios, and supporting regulatory or compliance assessments. However, where the decision problem involves long-term climate uncertainty, evolving demands, and threshold-based environmental objectives, deterministic outputs alone are insufficient. A bottom-up stochastic framework extends the value of existing models by using them to explore system response across a broader decision space. In doing so, it bridges the gap between model output and decision interpretation, bringing modelling closer to the questions that decision-makers need to answer: under what conditions do environmental objectives fail, how likely are those conditions, and which management strategies remain robust despite uncertainty?

The use of bottom-up assessment for environmental flow management

This paper presents a bottom-up stochastic modelling framework designed to support environmental flow management under deep hydroclimatic uncertainty. There is a growing body of literature highlighting the value of bottom-up approaches for decision-making under deep uncertainty, particularly in systems influenced by non-stationary climate conditions and structural change (Culley et al., 2016; Fowler et al., 2024; Guo et al., 2017). These approaches are well suited to problems where future conditions cannot be represented by a small number of discrete scenarios but instead require exploration of a wide range of plausible system behaviours. The framework is implemented using an established deterministic water balance model (eWater Source) that has been adapted to enable high-volume stochastic simulation (Figure 1). eWater Source is widely used for representing complex river systems, including multiple water sources, demand nodes, storages, and allocation rules.

The framework produces large ensembles of simulated system outcomes (i.e., pit lake filling duration, environmental flow compliance), which can be analysed to derive performance metrics, threshold exceedance probabilities, and empirical distributions of key hydrological and ecological indicators (Figure 2). By simulating many stochastic climate sequences alongside multiple climate change responses, the framework allows the separation of three key influences on system outcomes: natural hydroclimatic variability, longer-term climate change effects, and the incremental impacts of closure design and operational decisions. This decomposition is not possible under deterministic single-sequence approaches, where these interacting influences are collapsed into a single outcome per scenario.

This bottom-up stochastic modelling approach also improves the evaluation of complex management strategies. For example, a conclusion that environmental flow compliance criteria are consistently met may only hold under a narrow subset of climate sequences but may change substantially when assessed across a broader range of plausible conditions. Similar behaviour can be observed for mitigation measures, where effectiveness may depend on specific sequences of wet and dry periods or the presence of progressive climate change signals. These distinctions are more clearly identified when results are expressed as ensembles of simulated outcomes, enabling interpretation through distributions and probabilities rather than single values (Figure 3).

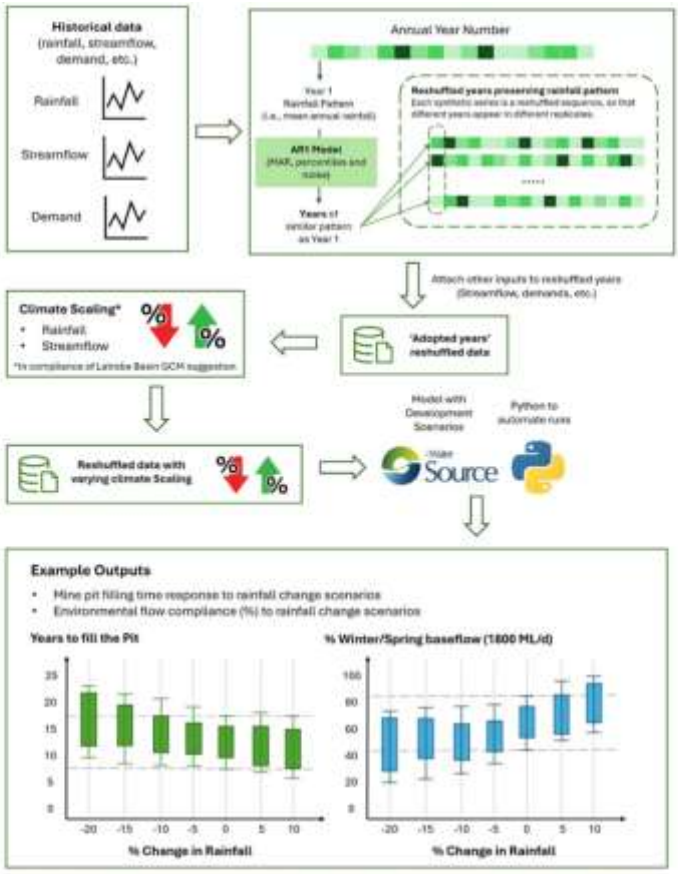

Figure 1 Conceptual workflow for stochastic water resource modelling, showing historical climate and demand data reshuffled into synthetic sequences, climate-scaled, run through Source, and summarised as pit-filling and environmental-flow response metrics

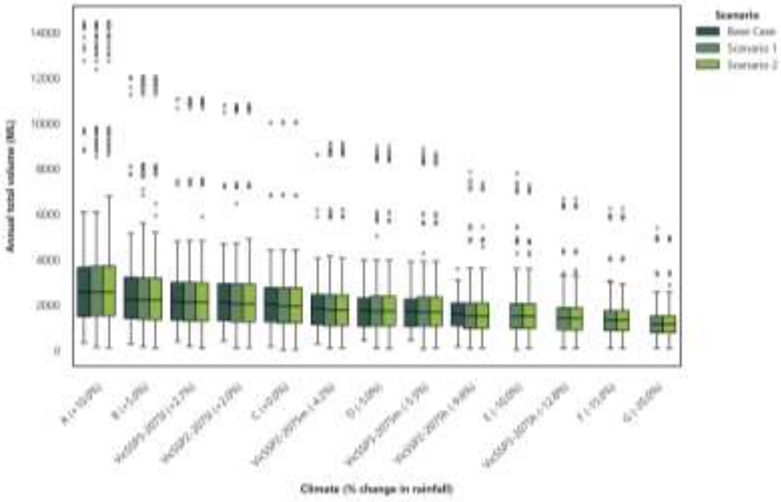

Figure 2 Example* outputs of catchment inflows to a receiving waterway under selected modelled scenarios, showing how catchment runoff shifts due to incremental shifts in climate (mean annual rainfall)

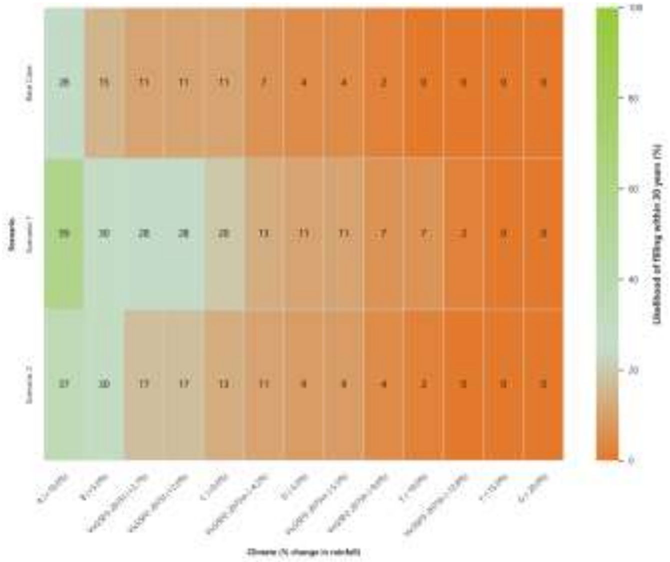

Figure 3 Example* outputs of a filling lake with a 30-year fill target under selected modelled scenarios, showing how achievement of the target shifts due to incremental shifts in climate (mean annual rainfall)

Previous assessments determined dry medium and wet year environmental flow achievement and produced large volumes of data that needed to be interpreted by ecologists or technical experts. Rule achievement tests common to environmental flow analysis have previously relied on analysis of historical data which has an embedded climate signal. This approach facilitates comparison of simulated scenarios under plausible future conditions, by providing statistical replicates that isolate the influence of a changing climate metric (% change in rainfall) (Figure 4). This approach is maturing in research and is beginning to be used more frequently in different contexts to provide deeper insights into system responses to selected change.

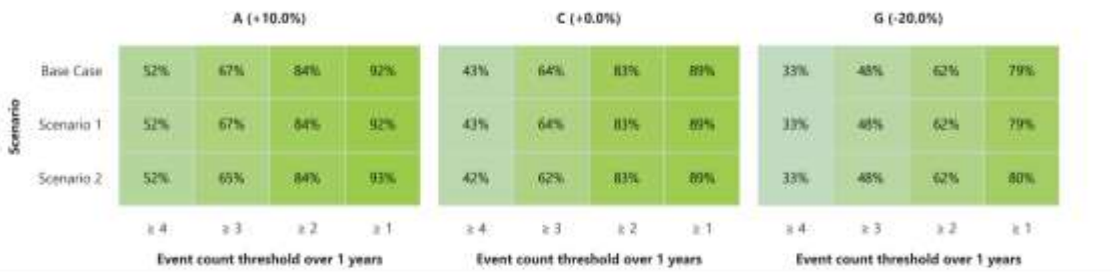

Figure 4 Example* outputs from environmental flow analysis under selected modelled scenarios shows how environmental flow compliance shifts under incremental shifts in climate (mean annual rainfall)

** Note: The results presented in the Figures 2-4 shown are illustrative examples only and do not present results from the modelling undertaken in this study.*

Example application of proposed framework – Yallourn mine rehabilitation

In the mine context, hydrological modelling refers to water resource and water balance modelling used to assess how closure demands may alter river flow regimes, environmental flow performance, and the water availability that supports environmental, agricultural, domestic, and industrial uses. Closure planning therefore requires understanding not only site-scale water behaviour, but also how reallocation or long-term use of surface water resources propagates through broader catchment systems. The proposed framework applies this bottom-up philosophy to mine closure water management by explicitly representing multiple sources of uncertainty, including climate variability and climate change, water supply and operational decision rules, future environmental system states and responses, and potential land use change. By incorporating these interacting uncertainties, the framework is able to test the robustness of alternative closure strategies across a wide range of plausible climate conditions and hydrological sequences, rather than relying on a single deterministic projection.

The Yallourn coal mine is located in the Latrobe Valley in Victoria, Australia, approximately 150 km east of Melbourne. It forms part of the broader Yallourn energy complex, historically associated with large-scale brown coal extraction and electricity generation in the region. The mine closure rehabilitation plan describes plans to fill interconnected mine voids using a combination of diverted river inflows and managed water transfers, ultimately creating a permanent interconnected pit lake system. Mine water use impacts the Morwell and Latrobe River system, meaning that closure operations must consider impacts to broader catchment values, environmental flow requirements, and competing water demands from other users and land uses in the region. This makes the system particularly sensitive to both climatic variability and operational water management rules, and decision-making must account not only for annual water balance, but also for the timing and routing of large flow events, interactions between river and pit-lake storage, and downstream compliance at key flow control points.

The Yallourn mine rehabilitation is a case study to demonstrate the applicability of the proposed framework. The environmental flow framework for this site is already well developed, with compliance points and flow requirements defined through the Latrobe environmental water requirements studies. This provides a clear and structured set of ecological performance metrics against which alternative closure arrangements can be evaluated. The key question in this study is how different closure strategies impact environmental flow achievement across a wide range of plausible hydroclimatic futures, and to what extent environmental flow objectives remain robust under combined climate variability, climate change, and operational decision uncertainty.

Implementation of the bottom-up stochastic framework

The framework was applied by updating the Latrobe Source model (DEECA 2024) to represent both the baseline system configuration and the proposed Yallourn rehabilitation design, including alternative mine conditions, pit-lake infrastructure configurations, interacting demands at adjacent sites, and operational assumptions relevant to closure planning. This established a consistent modelling platform on which alternative closure strategies could be evaluated under a common representation of regional hydrology, enabling systematic comparison of system performance under a wide range of hydroclimatic conditions. Once the base system was defined, the model was extended to support simulation of closure dynamics through time. Dynamic demand representation was implemented so that each simulation captured the full transition from pre-fill conditions through pit filling and into long-term pit lake operation. This avoids the need to split closure into separate deterministic phases, and instead allows water demands, storage behaviour, and operational rules to evolve continuously within each model run.

Hydroclimatic uncertainty was then represented using a large ensemble of stochastic climate sequences. To represent variability in rainfall and streamflow conditions, 50 stochastic replicates of climate sequences were generated as inputs to the Source model, allowing system behaviour to be evaluated across a much wider range of plausible hydrological futures. Climate change was incorporated into inputs as a transient signal rather than a static adjustment, with climate scaling factors progressively increasing from 0% in the initial simulation years to 100% by 2075. This allows gradual emergence of climate impacts within each simulation, rather than assuming an abrupt shift or fixed end-state condition. Additional sensitivity scenarios were also applied to explore structural response of key flow metrics, including rainfall perturbations ranging from +5% to −20%, linked to specific components of the flow regime used in environmental flow assessment.

For each climate signal (% change in rainfall) the input replicates were used to run the system model 50 times, and produce outputs that capture the simulated system response to changes in inputs. The comparison between like for like outputs therefore isolates the difference in climate variability between input sets, and the difference in a changing climate signal (a different % change in rainfall) between output sets.

Key insights

The Yallourn implementation shows that natural variability generates a wide range of plausible outcomes in its own right. Where compliance depends on the timing, persistence and clustering of events, a single deterministic ordering of years is not enough to characterise the spread of system behaviour. The use of 50 to 100 stochastic sequences exposes that spread. The stochastic approach also shows that climate change should be interpreted as a shift in the distribution of outcomes rather than as a uniform change in the magnitude or duration of some particular flow. Progressive climate scaling changes the position and spread of the outcome distribution (for example the number of years some compliance metric is achieved) through time, while the stochastic sequences preserve the year-to-year and multi-year variability that remains a controlling influence on system performance. This is consistent with the central argument of the paper: the impacts of climate change on overall water availability is amplified by natural variability, and the assessment needs to consider the compounding impacts of both delta shifts and changing seasonality on heavily impacted systems as is common in mine closure settings.

The framework also provides a stronger basis for comparing closure options than fixed-scenario modelling. Because outputs are expressed as probabilities, distributions and threshold exceedance metrics, the comparison is no longer limited to whether one option produces a higher or lower average effect under one adopted future. It becomes possible to compare how consistently each option performs across plausible futures, how sensitive each is to hydroclimatic sequencing, and how much of the observed risk is attributable to climate variability, climate change or closure arrangements.

Discussion and conclusions

Deterministic approaches remain the most commonly used method in mine water balance and closure planning studies, largely because they are well established in regulatory practice and are embedded within existing modelling frameworks that organisations have heavily invested in over time. There is often understandable hesitancy to move away from these approaches, as deterministic models are familiar, computationally efficient, and align well with traditional compliance reporting structures. However, previous deterministic assessments (on dry, medium, wet conditions), tend to produce large volumes of output that require substantial interpretation by ecologists and technical experts, and they can mask the full range of system behaviour under changing climate and operational conditions.

While deterministic methods still have an important role in baseline design and regulatory compliance, they are limited in their ability to capture deep uncertainty associated with climate variability, climate change, and evolving system responses. In contrast, stochastic and ensemble-based approaches are increasingly being recognised in research and applied settings as providing richer insight into system behaviour, particularly where decision pathways must remain robust under multiple plausible futures. This shift does not replace deterministic modelling entirely, but complements it by improving understanding of risk, variability, and long-term performance under uncertainty, ultimately supporting more informed and adaptive decision-making.

The results of this study show that a bottom-up stochastic approach provides clearer insight into system robustness by explicitly representing hydroclimatic variability, climate change trajectories, and closure design choices within a single analytical framework. This allows closure performance to be interpreted in terms of distributions and consistency across plausible futures, rather than relying on outcomes from a limited number of fixed scenarios.

However, in this application, the stochastic framework is implemented using an existing water balance model originally developed for deterministic simulation. The model has been adapted by introducing stochasticity through repeated simulations using externally generated climate sequences and scenario combinations. Although this approach enables large ensemble analysis, it also exposes a structural limitation: the rules and functionality embedded in the existing model are not necessarily well suited to stochastic simulation. As a result, reconceptualising the model and adapting it to a different methodological framework has been a challenging and onerous process. For example, running Source modelling software typically requires user interaction to initialise simulations. In this application, this process has been automated using Veneer, a Python-based API that enables Source to be run iteratively (Flow Matters 2014). While this automation supports the application of a bottom-up framework, adapting existing modelling tools in this way requires substantial effort. It can also reduce computational efficiency and constrain the ease with which more complex probabilistic or adaptive modelling structures can be explored. These limitations suggest that future work could benefit from the use of modelling platforms designed specifically for stochastic or ensemble-based simulation, where uncertainty propagation and scenario generation are more directly integrated into the model architecture. At the same time, deterministic climate scenario frameworks (including emissions-based pathways such as RCP or SSP projections) remain valuable for policy alignment and regulatory consistency. A combined approach, where scenario-based climate projections are evaluated alongside stochastic ensemble simulations, may therefore provide a more complete basis for assessing closure strategies under both structured climate pathways and deep uncertainty.

While this study has focused on mine rehabilitation within the Yallourn case study, the framework is not limited to closure planning applications. Mine closure provides a particularly demanding context because it combines long-term hydrological change, engineered flow controls, evolving water demands, and strict environmental flow requirements within a single regulated system. However, the underlying challenge is common to many water resources planning problems. As such, the bottom-up stochastic stress-testing approach demonstrated in this study can be transferred to other contexts where water systems are exposed to deep uncertainty and where decision-making depends on understanding robustness across a wide range of plausible futures rather than a small set of predefined scenarios.

More broadly, environmental systems are dynamic and continuously evolving under climate variability, climate change, and shifting land and water use pressures. In this context, information derived from modelling needs to move beyond single best-estimate projections or isolated scenario outcomes. Instead, it should provide explicit uncertainty bounds and a range of possible system responses, enabling decision-makers to understand not just what might happen under one assumed climate trajectory, but how outcomes vary across many plausible futures. This shift supports more resilient and adaptive planning by focusing attention on variability, risk exposure, and robustness rather than deterministic prediction.

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