Office of the Chief Scientist & Engineer

# Minimum Inflows Method Review

Technical review of a draft method for incorporating climate change information into the estimation of minimum inflows in regulated water sources.

# Final Report

**June 2025**

## Acknowledgement of Country

The Office of the NSW Chief Scientist & Engineer acknowledges the Traditional Custodians of the lands where we work and live. We celebrate the diversity of Aboriginal peoples and their ongoing cultures and connections to the lands and waters of NSW.

We pay our respects to Elders past, present and emerging and acknowledge the Aboriginal and Torres Strait Islander people that contributed to the development of this Report.

Erratum in the 2025 Minimum Inflows Method Review

| Page | Error | Correction |
|---|---|---|
| 7 | Overestimating the minimum volume of water can lead to overallocation of water resources to high security users, negatively affecting other water users and the environment. Conversely, underestimating minimum inflows exposes high security users to an unacceptably high risk of shortages. | Revised to 'Overestimating the minimum volume of water can lead to earlier and more frequent allocations of water resources to general security users, potentially negatively affecting priority water users and the environment if the inflow doesn't eventuate. Conversely, underestimating minimum inflows reduces initial allocations to general security water users but generally does not impact the end-of-year allocations available to these users.' |
| 27 | 72 **days** | 72 **months** |

**Note:** This version of the report was amended on 8 July 2025 to correct the above errata prior to public release. No changes have been made to the principles or recommendations made by the Expert Panel.

Minimum Inflows Method Review
Final Report
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24 June 2025

Parliament House
Macquarie Street
SYDNEY NSW 2000

**The Hon. Penny Sharpe MLC**
Minister for Climate Change
Minister for Energy
Minister for the Environment
and Minister for Heritage

**The Hon. Rose Jackson MLC**
Minister for Water
Minister for Housing
Minister for Homelessness
Minister for Mental Health
Minister for Youth
Minister for the North Coast

Dear Ministers,

**Re: Minimum Inflows Method Review**

In May 2024, you requested the Office of the Chief Scientist & Engineer (OCSE) to convene an independent expert panel (the Panel) to provide a technical review of a draft Method to estimate minimum inflows, used in making Available Water Determinations (AWDs) in regulated water sources.

The review of the periods of minimum inflows are a follow-up commitment to the NSW State Water Strategy (Action 4.2) to "Review water allocation and water sharing in response to new climate information". This OCSE Review of the draft method for revising estimates of minimum inflows sits within the NSW Government's commitment to the 2024 legal settlement with the Nature Conservation Council (NCC) to ensure future climate change is properly considered in Water Sharing Plans (WSPs).

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) has developed a draft Method for the broader 'Minimum Inflows Project', a component of which describes the methodology for incorporating climate change into estimates of minimum inflows (the focus of this Review). This uses paleo-stochastic climate scenarios adjusted for climate projections to determine the 'period of lowest accumulated inflows', with the assessment informing necessary changes to the accounting process for conducting AWDs.

An independent expert panel was established to provide a technical review and recommendations on the draft Method for estimating minimum inflows. The Panel was comprised of Associate Professor Fiona Johnson (UNSW Sydney), Professor George Kuczera (University of Newcastle), Owen Droop (OD Hydrology) and Dr Eytan Rocheta (Natural Resources Commission) and was Chaired by Dr Darren Saunders (NSW Deputy Chief Scientist & Engineer). OCSE provided Secretariat support and drafted the report.

If applied within the existing AWD decision-making process, the draft Method would improve on a significant limitation of the current approach for estimating minimum inflow sequences. DCCEEW has taken a critical step towards appropriately integrating climate change into AWD decisions. While there are some improvements that could be made to the draft Method, it represents a strong conceptual framework with which to deliver information on climate variability and potential climate change impacts on the estimates of minimum inflows that form part of the AWD decision-making process. However, the Panel emphasises that their findings and recommendations relate only to the information provided by DCCEEW within the scope of the Review.

I thank the Expert Panel members for their expertise and insights, and DCCEEW for providing information required in developing this advice.

Kind Regards

H. Durrant-Whyte

Hugh Durrant-Whyte

**NSW Chief Scientist & Engineer**

# Contents

## Acronyms

| Acronym | Description |
|---|---|
| ACTAQ | Advisory Committee on Tunnel Air Quality |
| AWD | Available Water Determination |
| CMIP | Coupled Model Intercomparison |
| $CO_2$ | Carbon Dioxide |
| DCCEEW | Department of Climate Change, Energy, Environment and Water |
| EEP | Extreme Events Policy |
| ET | Evapotranspiration |
| GC | Canopy conductance |
| GCM | Global climate model |
| GSE | General security entitlements |
| IPO | Interdecadal Pacific Oscillation |
| LAI | Leaf Area Index |
| MDBA | Murray-Darling Basin Authority |
| Mwet | Morton's Wet Area Potential Evapotranspiration |
| NARCliM | NSW and ACT Regional Climate Modelling |
| NCC | Nature Conservation Council |
| OCSE | Office of the Chief Scientist & Engineer |
| PET | Potential Evapotranspiration |
| PEW | Planned environmental water |
| QA | Quality assurance |
| QC | Quality control |
| RCM | Regional Climate Model |
| RWS | Regional Water Strategies |
| SSP | Shared Socioeconomic Pathways |
| TOL | Transmission and operational loss |
| TOR | Terms of Reference |
| WSP | Water Sharing Plan |

# Executive Summary

In May 2024, the Minister for Water, the Hon Rose Jackson MLC, and the Minister for Climate Change, Energy, the Environment and Heritage, the Hon Penny Sharpe MLC, requested that the Office of the Chief Scientist & Engineer (OCSE) convene an independent expert panel to provide a technical review (the Review) of a draft Method to revise estimates of the minimum inflows into public storages used in making available water determinations (AWDs) in most regulated water sources. The draft Method to estimate minimum inflows was developed by the Department of Climate Change, Energy, the Environment and Water (DCCEEW) in response to requirements to review how minimum inflows are defined and aims to ensure the period of lowest accumulated inflows is responsive to projected climate change impacts. The draft Method to estimate minimum inflows uses paleo-stochastic climate scenarios, adjusted for climate projections, to determine the 'period of lowest accumulated inflows'. This assessment will inform necessary changes to the accounting process for conducting AWDs.

This Review does not address the selection of a security risk level for priority water needs, consequent impacts on other water users or volumes of planned environmental water in regulated systems across NSW. Rather, it provides a technical assessment of the suitability of the draft methodological approach to revise minimum inflows modelling. Further, while the Review is not an examination of current policy or alternative policy approaches, the draft Method under assessment may support future changes to policy and/or legislation within a larger body of work being undertaken by DCCEEW ('Minimum Inflows Project').

The findings and recommendations of this Review support the initial steps taken towards incorporating climate change information into AWD decision-making, while also acknowledging that the approach sits within the broader body of work. Climate change poses ongoing and emerging risks and these should be accounted for through iterative improvements and adaptive management of the draft Method to estimate minimum inflows.

## Findings

### Overall observations

- Climate change is expected to have significant impacts on rainfall, temperature and evaporation. Current water allocation methods use a fixed subset of historical data that does not adequately incorporate these climate change impacts.
- DCCEEW proposes incorporating climate risk into estimates of minimum inflows via the use of paleo-stochastic data and the creation of time series for scenario modelling that represent possible future climates.
- The Panel has provided a technical review of the draft Method proposed for estimating minimum inflows. These methods form part of a broader, still-evolving draft framework for the 'Minimum Inflow Project', which was incomplete at the time of the Review.
- The draft Method for estimating minimum inflows lacked some detail and additional information was also delivered ad hoc, making it difficult for the Panel to form a consensus understanding of key details. The findings presented in this Review reflect the Panel's understanding and interpretation of the information as provided by DCCEEW only at the time of this Review.
- The draft Method was developed to be initially trialled in two regulated river water sources – the NSW Border Rivers and the Murrumbidgee River – with the intent of subsequently applying it across other valleys. At this point, the Panel can only comment on the application of the draft Method on the Border Rivers as this was the focus of the material provided.

- The use of climate-adjusted paleo-stochastic data to incorporate climate change into the minimum inflows is adequate in the short term but should be continuously improved through evidence-based adjustments.
- The proposed approach transitions from using a defined minimum inflow to generating a range of minimum inflows based on level of risk.
- The conceptual framework within the draft Method produces technically appropriate datasets and methods for the intended purpose of the draft Method, which is to provide improved information on minimum inflows under historic and potential future climate-change scenarios.
- Implementation of the draft Method in each valley will require a number of discretionary decisions. Operationalising the use of revised minimum inflows within the AWD process could apply the current AWD method. However, DCCEEW is proposing significant revisions to the AWD method which are outside the scope of this review and so the Panel is not able to comment on its use.
- The Panel notes that revisions to the estimates of minimum inflows represents only one component that informs AWD decision-making.

### Chapter 2: Panel interpretation of the draft Method

- The Panel's understanding and interpretation of DCCEEW's draft Method for the Minimum Inflow Project reflects information available at the time of the Review, as provided in documents and verbal briefings. Slide decks used in these briefings are not publicly available.
- DCCEEW sought to develop a draft Method that does not presume a particular supply reliability target and instead models the range of supply reliability. OCSE has only fully reviewed the draft Method to estimate minimum inflows, which forms part of the broader Minimum Inflows Project.
- The draft method to estimate minimum inflows aims to test model scenarios and storage reserve assumptions under historic and plausible future climate variations, using series 1-5:
    - Series 1-3 use instrumental historic series and the 10,000-year paleo-stochastic climate dataset for determining the baseline minimum inflow dataset.
    - Series 4 and 5 modify the paleo-stochastic climate series using NSW and ACT Regional Climate Modelling (NARCliM) scaling factors to represent current and near future climate minimum inflow possibilities.

### Chapter 3: Historical climate data

- Using paleo-stochastic climate data with a 10,000-year record (incorporating more severe low flows than those currently considered) provides a broad range of historically based climate conditions to inform water management, allocation decision-making, and the reliability of current policy approaches. This is a transparent approach to determining high-security reserve and is an advancement compared to using historical climate data alone.
- Climatic sequences are stochastically generated based on observed statistics, including the seasonal mean and standard deviation, and the annual serial correlation (a measure of how wet or dry a year is based on the previous year) to improve the representation of extreme events. Low frequency variability is embedded through the generation of a stochastic sequence representing Interdecadal Pacific Oscillation (IPO) phases.
- There is an increasing temperature trend in the northern inland Murray-Darling Basin and statistically significant increases in temperature and decreases in cool season rainfall in the southern inland Murray-Darling Basin. Therefore, DCCEEW incorporated temperature changes into the climate data used in the minimum inflows project in the northern Basin, with further consideration given to rainfall changes in southern Basin.

- DCCEEW's approach to considering potential non-stationarity in climate data is appropriate for ensuring the draft Method does not underestimate climate change impacts on estimates of minimum inflow.
- DCCEEW's approach may be oversimplifying climate change in the longer term by only focusing on rainfall and potential evapotranspiration (PET) and excluding changes to processes in the landscape and vegetation.

### Chapter 4: Climate change data

- DCCEEW's approach to incorporating NARCliM projections with paleo-stochastic data produces a range of minimum inflows incorporating climate change information which could inform AWD decision-making.
- There is significant uncertainty in projected rainfall scenarios arising from both the underlying climate models and the choice of emission scenario.
- Given that elevated temperatures are already being observed globally, it is a reasonable approach to run scenarios based on increased PET. This supports the use of Series 4 as the 'base case' for estimating minimum inflows rather than unadjusted paleo-stochastic data.
- The documentation (draft Method and supporting information) switches between using terminology of evapotranspiration (ET) and PET.
- The selection of Shared Socioeconomic Pathways (SSP) 3-7.0 (high emissions) over SSP2-4.5 (medium emissions) or SSP1-2.6 (low emissions) may not ultimately impact the near-term ET scaling approach for Series 4 but may for Series 5. An analysis of scaling factors for each scenario would provide transparency on the magnitude of the differences.
- It is unclear how the climate data will be used to scale the 10,000 years of paleo-stochastic data – it is not explicitly stated whether the full ensemble of NARCliM models will be used to derive the scaling values or if a single model will be used.
- The timeframe selected for Series 4 (2035) *is appropriate for reflecting climate conditions to* inform minimum inflows over the life of the Water Sharing Plan (WSP).
- The timeframe selected for Series 5 (2050), while arbitrary, is appropriate for informing an adaptive pathway and providing stakeholders with an indication of potential future changes to minimum inflows. The timeframe needs to be considered as adaptive because in 10 years' time, 2050 will be close enough to the planning horizon that the stress test could become the design.
- The Series 5 stress test should be used to communicate and frame future risks to minimum inflows. However, it is unclear how Series 5 will be used in the draft Method. It is not appropriate to describe the stress test as a 'worst case' scenario as it does not represent the commonly used understanding of worst case due to several uncertainties and assumptions.
- Split sampling was not used in the calibration of DCCEEW's rainfall-runoff models. By assuming long-term stationarity, the draft Method to estimate minimum inflows overlooks the importance of accounting for non-stationarity, such as vegetation-driven changes in ET due to climate change. Split sample testing can provide a more holistic approach in modelling inflows.

### Chapter 5: Climate change and AWD decision-making

- The models are reasonably calibrated for their intended purpose, which is to assess the bulk hydrological mass balance under a repeat of historical climate conditions to determine if there has been growth in use.
- Calibration of low flows in the models have some limitations. They may not appropriately capture increases in water losses, such as evaporation and infiltration, that occur during

extended low flow conditions, particularly those at and beyond the extreme dry end of historically experienced climatic conditions.

- Where river system models do not appropriately represent drought conditions, DCCEEW proposes compiling inflow volumes associated with a range of return periods to estimate minimum inflows.
- These return period tables provide DCCEEW with a matrix for decision-making. With this, it is possible to estimate minimum inflows at an acceptable level of risk over an appropriate planning duration.
- The return period tables can be used as an interim solution for moving towards a more risk-based approach.
- The process for how the minimum inflows draft Method will provide data that can operationalise climate risk into AWD decision-making is still evolving.

## Recommendations

### Recommendation 1: Prioritise short- to medium-term improvements to the Method including climate datasets, rainfall runoff models and adaptive management

**Recommendation 1.1 (short term):** Increase the level of detail in the Method describing climate data and modelling, inputs, assumptions, and determining biases of data and how they will be considered. This information should be included in relevant documents in the initial or first version. Subsequent iterations to the Method for estimating minimum inflows should be published as discrete versions, as opposed to as an evolving draft within the broader Minimum Inflows Project. The Method should contain enough technical and scientific detail to be reproducible.

**Recommendation 1.2 (immediate and ongoing):** Identify possible sources of systemic compounding bias by validating modelled data against instrumental data, with a particular focus on model performance over extended periods of low flow. Publish information and methods taken to address biases. If observed conditions fall outside a pre-identified range, a review of the Method should be triggered to determine causes of the discrepancy and potential improvements.

**Recommendation 1.3 (short term):** Given that the concept of seasons is arbitrary, PET in Series 4 & 5 and PET and rainfall in Series 5 should be scaled using monthly factors to ensure that future changes in variability are not excluded in the scenario.

**Recommendation 1.4 (medium term):** Investigate whether sampling of the paleo-stochastic data, conditional on IPO state, will lead to different short-term estimates of minimum inflow than those made using the full 10,000-year record.

### Recommendation 2: Adaptively manage the Method for estimating minimum inflows. Continue to refine the Method over the longer term by establishing a framework that is adaptively updated as new information becomes available

**Recommendation 2.1 (ongoing):** Ensure the Method is considered an adaptive framework. Set trigger points that prompt adjustments to the estimation of minimum inflows, such as plan suspensions or minimum inflows below the modelled range. Update data underpinning minimum inflows with relevant climate-scaled paleo-stochastic data as newer NARCLiM versions become available.

**Recommendation 2.2 (long term):** Incorporate changes into rainfall runoff models for the surrounding landscape and vegetation affected by increasing atmospheric carbon dioxide ($CO_2$).

**Recommendation 2.3 (short term and ongoing):** Convene a standing Expert Panel to advise on the ongoing revision of processes related to estimating minimum inflows and their incorporation into AWD decision-making processes. This Panel should consist of professionals with relevant expertise, be independent of DCCEEW and the Water Group, and operate in an advisory capacity to ensure that evidence-based guidance informs decision-making on a continuous basis. This panel could also provide ad hoc advice on specific technical aspects of the Methods as needed, particularly when applying them across different valleys.

**Recommendation 2.4 (long term):** The NSW Government should provide a long-term commitment through appropriate resourcing of DCCEEW's efforts to ensure an adaptive approach to the incorporation of climate change into water management practices in NSW.

**Recommendation 2.5 (short term and ongoing):** Use multiple lines of evidence to continue to inform estimates of minimum inflows by finding the most suitable data using both model outputs and return period table outputs and clearly defining confidence intervals for both.

**Recommendation 3: Improve transparency on methodological details around terminology and scenario usage, and provide clear communication to decision-makers and stakeholders**

**Recommendation 3.1 (short term):** Clearly communicate to decision-makers that the estimates of minimum inflows are not a forecast but rather form an adaptively managed process which can provide guidance for adjusting AWD decision-making to reflect a changing climate.

**Recommendation 3.2 (short term):** Use explicit terminology and language in the Method to improve clarity. For example, documentation should be consistent and explicit that the Method uses PET in the rainfall runoff modelling.

**Recommendation 3.3 (short term):** Prioritise effective communication and framing of uncertainty with Series 5 'stress testing' and make outputs public so that stakeholders are adequately informed of proposed changes to minimum inflow estimates.

**Recommendation 3.4 (long term):** Provide greater transparency around the work undertaken to operationalise climate risk in minimum inflows in the AWD decision-making process to build stakeholder trust and confidence.

# 1. Introduction

## 1.1 Background

NSW water resources face pressures from a changing, more variable climate and increasing needs for secure and sustainable water supplies for growing populations and industry (NSW DPIE, 2021). There are significant stakeholder concerns about climate change impacts and the suitability of the current allocation method to provide an appropriate level of security for priority water needs. Management of regulated river water sources requires improved understanding of historic climate variability, future climate change and associated risks to inform implementation of strategies that sustainably share water between various uses such as town water supply, irrigation, industry and the environment.

An improvement in managing water resources involves incorporating climate risks into AWD decision-making. One component of the AWD process is the assumption that the volume of water flowing into headwater storages over the coming year will exceed a predetermined minimum volume, also known as minimum inflows or lowest accumulated inflows. Overestimating the minimum volume of water can lead to earlier and more frequent allocations of water resources to general security users, potentially negatively affecting priority water users and the environment if the inflow doesn't eventuate. Conversely, underestimating minimum inflows reduces initial allocations to general security water users but generally does not impact the end-of-year allocations available to these users.

In response to these concerns the Department of Climate Change, Energy, the Environment and Water (DCCEEW):

- Committed to "review water allocation and water sharing in response to new climate information" under Action 4.2 of the NSW State Water Strategy (NSW DPE, n.d.). This review consists of four main components:
    1. a review of elements in the water allocation process, particularly the assumptions relating to expected inflows, and a consideration of amendments that could incorporate climate change and provide a clearer understanding of water supply risk
    2. an impact assessment using scenario modelling that focuses on water balance, environmental and economic assessments
    3. an options analysis
    4. stakeholder engagement over shortlisted options.
- Developed the 'Minimum Inflows Method' (Table 1) to review estimations of minimum inflows for nine inland regulated river Water Sharing Plans (WSPs) (Appendix 2).
- Amended relevant WSPs to include provisions specifying requirements for the Minimum Inflows Method.

The NSW Government also committed to addressing a 2024 legal settlement with the Nature Conservation Council (NCC) which requires that climate change risks are properly considered when reviewing or remaking WSPs. In line with the Ministers' legal obligations, in May 2024, the Office of the Chief Scientist & Engineer (OCSE) was requested by the Minister for Water, the Hon Rose Jackson MLC, and the Minister for Climate Change, Energy, the Environment and Heritage, the Hon Penny Sharpe MLC, to convene an independent expert review panel (the Panel) to provide a technical review (the Review) of the component of the 'Minimum Inflows Method' used to estimate minimum inflows (see Terms of Reference (TOR) in Appendix 1).

The draft Technical Review Method (referred to as the draft Method; see Appendix 2) was developed by DCCEEW to outline the broader methodology for assessing water supply risks under climate change. It forms part of the DCCEEW Minimum Inflow Project, which aims to review how minimum inflows are considered in the AWD decision-making process.

The draft Method includes an approach for estimating minimum inflows using paleo-stochastic datasets adjusted for climate risk, which is the focus of this Review (hereafter referred to as the draft Method to estimate minimum inflows; see Table 1). It is accompanied by an approach to validating climate risk data for use in WSPs (Appendix 3)

The draft Method, including the draft Method to estimate minimum inflows, is still under development. Ad hoc information was also provided to the Panel (see Appendix 4 for a full list), although not all of it was relevant to the scope of this Review.

### 1.1.1 Scope

OCSE was asked to provide advice on the suitability of the draft Method for estimating minimum inflows for operationalising climate risk into AWD decision-making through:

- Reviewing the suitability of the stochastic datasets used in the draft Method that feed into the broader AWD process
- Reviewing the suitability of DCCEEW's approach to incorporate climate change into the draft Method for estimating minimum inflows
- Providing recommendations for improvements to DCCEEW's draft Method which can be applied in the short and medium term.

The following were specified as out being of scope for this Review and not subject to comment by the Panel:

- The selection of risk level of security for essential requirements, including consequent impacts on other water users and planned environmental water in regulated systems across NSW
- Review of DCCEEW's river system models of the regulated river water sources used for these assessments
- Review of other aspects of the AWD method, including the calculation of losses and reviewing entitlement volumes
- Potential impacts on entitlement holders.

Specifically, the Review is a technical scrutiny of the robustness of DCCEEW's draft Method to estimate minimum inflows, including the suitability of climate data and method of incorporating this data into minimum inflow estimation. The Review is not an examination or assessment of current or alternative policy or legislative approaches. However, information from this Review could be considered in any future review of policies and legislation.

## 1.2 Role of minimum inflows in water allocation in NSW

### 1.2.1 Available Water Determinations (AWDs)

Water in government-owned storages in regulated river systems is distributed via an AWD process governed by the *Water Management Act 2000*[1], *Water Management (General) Regulation 2018*[2] and provisions specified in relevant WSPs. The process conducted for AWDs is implemented by the Water Group in DCCEEW with support from WaterNSW and documented in protocol documents published by DCCEEW. The AWD process uses an accounting method to reserve an amount of water to secure supply for priority water needs.

[1] *Water Management Act 2000* (NSW) (*"The Act"*)

[2] *Water Management (General) Regulation 2018* (NSW)

In quantifying the amount of water expected to be available, WSPs require the water supply system to be operated in such a way that water would be able to be supplied during a repeat of the period of lowest accumulated inflows to the water source, to meet priority requirements including basic landholder rights and domestic and stock access licences, local water utilities and high security access licences. Other plan provisions require planned environmental water (PEW) provisions to be provided before high security allocations meaning PEW is also included in the priority requirements. Current WSPs specify the period of lowest accumulated inflows to the water source to be identified by flow information held by DCCEEW prior to a particular date. For example, the WSP for the *NSW Border Rivers Regulated River Water Source 2021*[3] states "flow information held by the Department prior to 1 July 2009".

AWDs are the mechanism for providing new water allocations to entitlement holders' accounts and are issued through notifications published on DCCEEW's website. AWDs are generally issued at the start of the water year (1 July) and continue to be issued throughout the year if water availability improves until allocations reach the maximum allowable amount.

In NSW, high security water users hold licences that give them a higher priority to access water through allocations than general security licences, particularly during periods of water scarcity. Due to their increased reliability, high security licenses are generally more applicable to water users who require annual water for town water supply, horticulture, mining, industrial use, aquaculture or environmental needs. Full or near-full high security water allocations are made at the start of the year (except for in very dry years). In contrast, general security allocations are usually only made after high security receives their full entitlement and as such, during dry conditions can receive low-to-zero initial allocation.

For valleys in the northern Basin, the volume of water available for allocation is calculated based on a water mass balance over a specified planning horizon. This mass balance (Equation 1) includes water available in headwater storages, an estimate of assumed future inflows, a priority reserve to secure priority water needs, existing commitments (such as carryover), and estimates of evaporative losses from storages and transmission and operational loss (TOL).[4] [5]

**Equation 1:**

*Available resource = (Current Storage + Assumed Inflows) – (Priority Reserve + Commitments + Losses)*

To reduce the volume of water required in headwater storages for future priority water needs and to enable larger initial allocations to general security entitlements, the assumed future inflow is subtracted from the volume of the priority reserve. As such, the volume of water available in the priority reserve is insufficient to meet all priority water needs but is topped up as inflows occur over the planning horizon (NSW DPE, 2022). This process of allocating water that is not yet available in the system has been described as a "credit" approach which places risks on priority needs if expected inflows do not eventuate, or if actual losses exceed those allowed for. These risks have led to the adoption of an estimate of inflows which is based on the minimum inflows that have occurred in the plan areas over the historic record over a set time frame in an attempt to be more conservative. Notably, this time frame does not usually include the most recent severe droughts (e.g. the Millennium [2001- 2009] and Tinderbox [2017-2020] droughts). More detail about how DCCEEW

[3] *Water Sharing Plan for the NSW Border Rivers Regulated River Water Sources 2021*

[4] Losses or system overheads include evaporation from storage, delivery and transmission losses, and other operational losses and vary based on antecedent and current hydroclimate conditions.

[5] The general AWD calculation in all valleys is: (Current storage reserve + future inflow) - (Priority reserve + Commitments + losses)

approaches the relationship between storage reserves and minimum inflows can be found in section 2.2.2 of the draft Method (Appendix 2).

Various approaches are used across different jurisdictions in Australia and abroad that reflect differing levels of risk applied to prioritising the supply of priority water needs. For example, the Murray-Darling Basin Authority (MDBA), which operates the Southern-Connected Basin, implements an approach where inflow scenarios are provided to states to select the level of risk to apply to priority water needs. NSW chooses the 99th percentile for the Murrumbidgee and Murray systems which excludes the droughts occurring after the commencement of the plans in 2004. South Australia has embraced recent, more severe droughts by choosing the worst-case scenario when allocating water, while Victoria has chosen to be even more conservative by adopting the worst-case inflow for three months with zero inflow thereafter.

### 1.2.2 Need for an updated approach to estimating minimum inflows

Current WSPs specify that the 'minimum inflow sequence' is identified by information held by DCCEEW prior to the start of the first WSP in that water source. In many cases, this excludes consideration of recent droughts in the allocations process, likely underestimating the impact of climate change on the potential for lower inflows than experienced historically. The consequence of this is the potential for allocations to be determined based on projected inflows which are higher than actual inflows, increasing risks of overallocation and of shortfalls for priority water needs since there is less actual water available than planned for under the AWD assumptions.

To put this in perspective, all regulated WSPs (except for the Border Rivers, Peel and Belubula WSPs) in scope of this Review use a minimum inflow sequence based on "flow information held by the Department prior to 1 July 2004", indicating that only data from last century is being used to underpin AWDs. However, since 2004, there have been more severe droughts, including the Millennium [2001-2009] and Tinderbox [2017-2020] droughts. Both caused record low inflows into some water storages, triggering multiple 'plan suspensions'[6] and/or the implementation of the Extreme Events Policy (EEP) (NSW DPE, 2023a). This caused uncertainty for water users and severe environmental impacts, including a marked decline in wetland wildlife in the Murray-Darling Basin (Leblanc et al., 2012) and the death of iconic drought-tolerant tree species such as the River Red Gum over extensive areas (Armstrong et al., 2009). Further, drought significantly impacts cultural heritage by disrupting traditional practices and degrading scared sites and hinders First Nations Peoples' connections to Country and their strong alignment to water (Rigby et al., 2011).

It is important to note that a reduction in the volume of assumed minimum inflows due to incorporating flow information from more recent droughts may have two potential effects:

1. Improved security for priority needs
2. Adverse impact on general security entitlements (GSE) through changes in timing of allocation announcements.

An amendment was made to legislation in 2014 following an internal Departmental review of the minimum inflows assumption after the Millennium drought. This amendment allowed for the worst drought occurring prior to the commencement of each of the current water sharing plans to continue to be used to determine the minimum inflow and thus the size of the priority storage reserve[7]. At the time, this amendment was described as maintaining the water shares between the environment, high security licences and general security licenses as agreed when the water sharing plans were first developed[8] .

[6] *The Act* s 49B

[7] *Water Management Amendment Bill 2014* (NSW)

[8] New South Wales, *Water Management Amendment Bill 2014*, Legislative Assembly, 29 May 2014

In practice, this meant that in the instance of the 2021 Border Rivers WSP[9], a minimum inflow sequence for the period prior to the 2009 Border Rivers WSP was adopted. DCCEEW is now aware that minimum inflows during the 2017-2020 drought were lower than those estimated from the pre-2009 record. Incorporating out-of-date climate information into the minimum inflows process risks misrepresenting expected minimum inflows, leading to allocations to GSE that should be reserved for town water supplies or the environment to cope during droughts. Embedding up-to-date information into the process for making decisions around reserving and allocating water through updated minimum inflow estimates avoids overallocation and protects town water supplies and the environment in drought times.

Therefore, an objective, data-driven approach to incorporating modern drought data and future climate variability into estimates of minimum inflows overcomes the main limitation with the current approach, which relies on recorded drought data that fails to recognise increasing risk to water security for priority uses due to climate change. Additionally, if recent droughts are not considered in setting minimum inflows, water allocations are biased due to less severity in:

- Past historical droughts compared with more recent droughts observed using gauges
- Droughts during the instrumental period (~100 years) compared with droughts that occurred prior to the start of gauging
- Past historical droughts compared with future droughts given the expected impacts of climate change on future rainfall, temperature and evaporation (NSW DPIE, 2020).

Basing estimates of minimum inflows on a limited portion of historical data alone, and excluding recent record droughts, results in a process which does not represent the likely range of risks faced by priority water needs. If this approach continues to be used and climate conditions change from those observed in the historical record (by gauges) as predicted, then minimum inflow estimates will not reflect the changed and changing hydrology of the system. Subsequently, responsive actions such as implementing the EEP or plan suspensions may be required more commonly to address instances of overallocation.

The remainder of the Review addresses the scientific aspects of DCCEEW's draft Method for incorporating climate change information into minimum inflows to inform the AWD process.

## 1.3 Review Process

The process for this Review followed established OCSE principles and procedures for independent reviews (Figure 1). OCSE established an Expert Panel (the Panel) based off specific skills identified against a desired skills matrix, including experience with AWDs, climate modelling, surface water, hydrology, risk assessment and uncertainty. The role of the Panel was to participate in Panel meetings, including consultations with DCCEEW staff and provide advice on issues relevant to the TOR. The Panel was comprised of:

- Dr Darren Saunders (NSW Deputy Chief Scientist & Engineer, Panel Chair)
- Owen Droop (OD Hydrology)
- Associate Professor Fiona Johnson (UNSW Sydney)
- Professor George Kuczera (University of Newcastle)
- Dr Eytan Rocheta (Natural Resources Commission)

The Panel was provided with two primary documents to inform this Review:

- Draft paper *Technical Review Method* provided by DCCEEW (Appendix 2)
- Draft paper *Validating climate risk data for use in Border Rivers water sharing* (Appendix 3)

[9] *Water Sharing Plan for the NSW Border Rivers Regulated River Water Sources 2021*

The draft Method provided to the Panel was still in early draft form. The Panel requested additional technical information from DCCEEW to supplement the draft documents. The full table of documents and information provided is in Appendix 4.

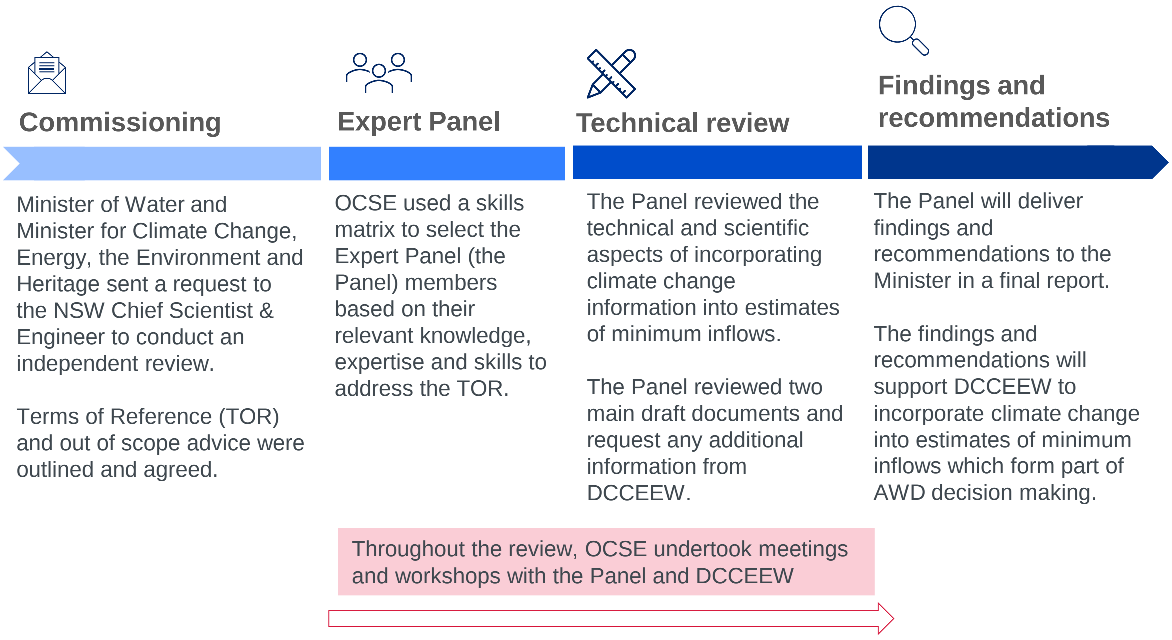


*Figure 1. Overview of the Review Process*

### 1.3.1 Review outline

The chapters in this Review discuss the components of DCCEEW's draft Method for estimating minimum inflows and how it fits into the broader AWD process.

Chapter 2 provides an overview of the Panel's interpretation of DCCEEW's draft Method to use paleo-stochastic data and climate change modelling to inform minimum inflows.

Chapter 3 discusses the baseline climate series used for scenario modelling (TOR 2) that can be used to incorporate historic climate information into estimates of minimum inflows, including historical instrumental climate data over different time periods and 10,000-year paleo-stochastic data (Series 1-3).

Chapter 4 introduces climate change series for scenario modelling (TOR 3) through scaling the 10,000-year paleo-stochastic climate sequence with different NSW and ACT Regional Climate Modelling (NARCliM) emissions scenarios (Series 4-5).

Chapter 5 assesses the suitability of the draft Method for operationalising climate risk into AWD decision-making (TOR 1) by investigating how the approaches outlined for evaluating minimum inflow sequences in Chapters 3 and 4 are practically used.

*Table 1. Scope of the Review for methods proposed by DCCEEW to incorporate climate change in minimum inflow estimates, in the context of the broader 'Minimum Inflows Project'.*

"Minimum inflow project' presented to panel

| | Minimum inflow method | | | AWD method | | | AWD operationalisation | |
|---|---|---|---|---|---|---|---|---|
| | Policy | Data | Method | Policy | Data | Method | Other potential climate change policy responses | Issuing AWDs |
| Current | **Based on historic instrument / observational data*** | **Historical (pre-inaugural plan)*** | **Rainfall runoff model*** | Priority reserve<br><br>Generally 2 years guaranteed supply<br><br>Worst historical case<br><br>Limited discretion | Demands<br><br>Losses<br><br>**Minimum inflow (TOR 1)*** | Water balance | Extreme Event Policy (EEP)<br><br>Plan suspensions<br><br>Negative allocations<br><br>Range of other policy options | Allocations<br><br>Impacts on other uses including Planned environmental water (PEW)<br><br>Compliance with Act<br><br>Discretionary decision-making |
| Proposed | **Based on paleo-stochastic climate data + climate change data*** | **Paleo-stochastic climate data + climate change data*** | **Paleo (reviewed-previous OCSE review)***<br><br>**Shared Socioeconomic Pathways (SSP) → Global Climate Models (GCM) → Regional Climate Model (RCM - NARCliM) (TOR 3)***<br><br>**→ scaling factors → Rainfall runoff model (TOR 2)*** | Priority reserve<br><br>Unknown guaranteed supply<br><br>Risk based<br><br>Ministerial discretion | | Water balance<br><br>Hydrological model | | |

Legend: In-scope of review (**bold text** with blue shading and * symbol) Out-of-scope (grey shading)

# 2. Panel interpretation of the draft Method for estimating minimum inflows

Currently, minimum inflows in each valley are calculated using a rainfall runoff model based on historical data up to the start of the first water sharing plan for that valley. The lowest accumulated inflow over a fixed period (generally two years or less) becomes the minimum inflow that is used in the AWD process. The draft Method proposed by DCCEEW aims to integrate climate change information into the methodology through two key modifications:

- Technical changes in the input data for rainfall runoff models.
- Procedural changes in the approach to identifying the minimum inflow that may require a policy or legislative change, i.e. shifting from a fixed requirement to store sufficient water to provide for an estimated time for priority water needs, to a risk-based approach based on a range of potential minimum inflow scenarios.

Changes to the data inputs will involve replacing observed historic data with time series based on the 10,000-year paleo-stochastic dataset to represent plausible historic climate data. In addition, climate information from selected emissions scenarios and climate models in the NARCliM project will be used to determine scaling factors that will be applied to scale precipitation and evaporation variables in the paleo-stochastic dataset to reflect potential climate change scenarios. Modelled storage inflows over the 10,000-year record will then be generated via a rainfall runoff model by:

1. Extracting rainfall and evaporation data for areas upstream of the major storages relevant to inputs to the rainfall runoff models.
2. Simulating inflow sequence by modelling rainfall runoff with hydroclimate inputs (rainfall and evaporation) over the 10,000-year time series. Assumptions do not account for contributions from downstream unregulated inflows, rainfall or runoff included in some operational AWD processes.
3. Evaluating statistical characteristics compared with runoff generated using the instrumental record. In cases where discrepancies in statistical characteristics are deemed too high, DCCEEW have identified they will qualitatively interpret the results, taking any bias into account, but have not provided details of this approach.

The Panel consider that the proposed revised technical approach could be implemented into the current method for identifying the minimum inflow. This would satisfy the aim of operationalising climate information into the determination of minimum inflows and improve the level of climate information and climate risk in this aspect of the AWD process. The Panel supports the need for a risk-based minimum inflow determination.

However, DCCEEW is also proposing a change to the incorporation of minimum inflows into the AWD decision-making process whereby there is no explicit determination of the minimum inflow. Instead, a proposed procedural change which may require changes in policy or legislation related to the AWD decision-making process incorporates a range of potential minimum inflows which will be used in a risk-based approach. The risk of shortfall in priority uses will be determined by aggregating the 10,000-year modelled inflow record alongside other parameters that feed into the AWD process into periods ranging from 6- to 72-months and then calculating the frequency of occurrence (as percentiles) of shortfalls. The aggregation method was not finalised at the time of this review and DCCEEW were still considering implementation details including whether months used in early sequences were to be included or excluded from each new aggregation. Potential changes to the AWD method are beyond the scope of this review but the Panel believes the proposed changes to the AWD process (and potentially policy or legislation) should be subject to peer review.

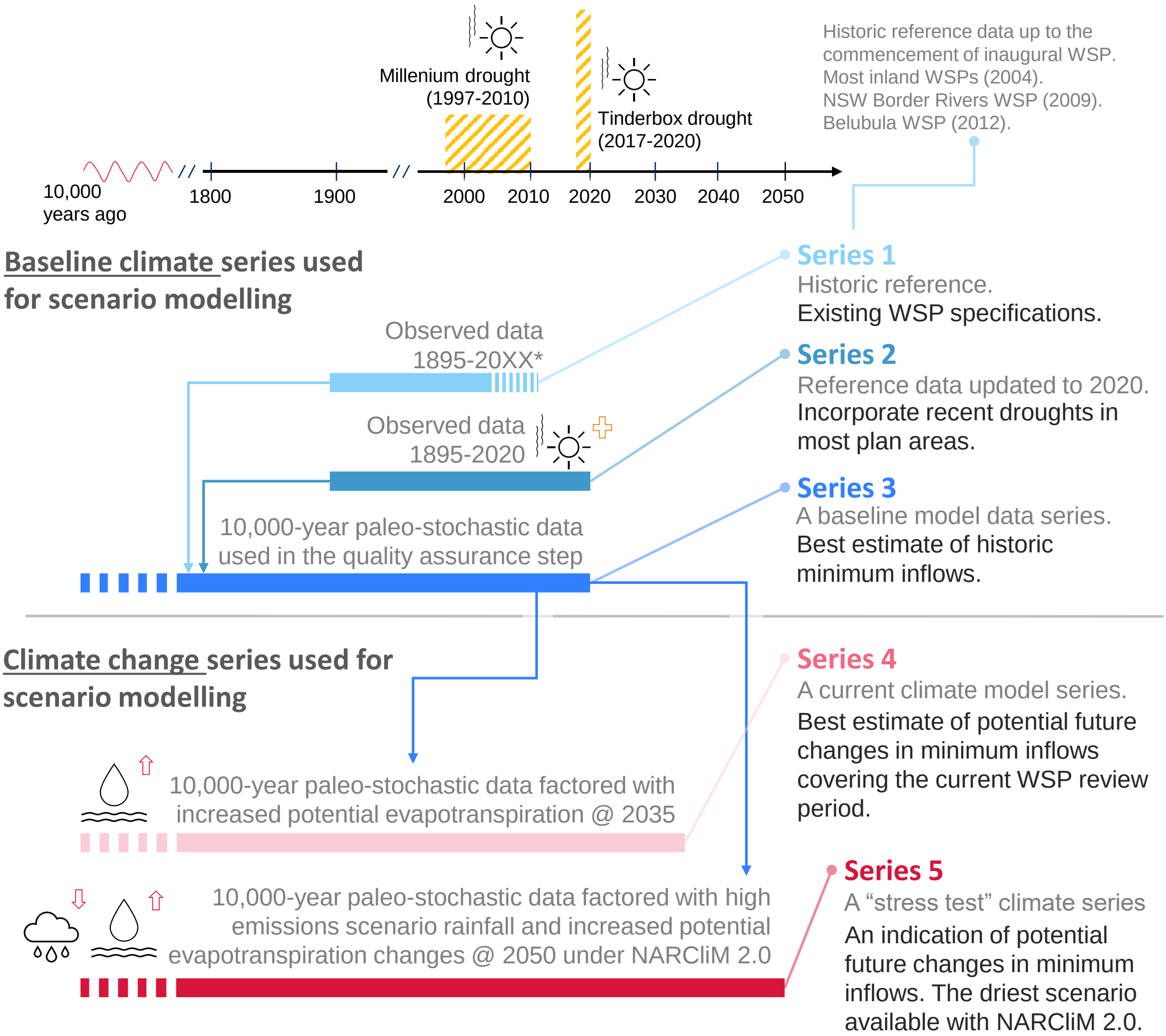


*Figure 2. Datasets and chapters*

# 3. Historical climate data

DCCEEW's draft Method applies scenarios for historic and future climate variations to provide an indication of potential changes in minimum inflows (Figure 2). This chapter addresses the approach to historical data (Series 1-3), as covered by TOR 2:

- Series 1 data covers historic instrumental/observational climate data up to the cutoff date based on the commencement of the inaugural WSP. For most inland regulated WSPs, this date is 1 July 2004. However, in the NSW Border Rivers and Belubula it is 2009[10] and 2012[11], respectively.
- Series 2 data is used to calibrate the stochastic model that generates Series 3 and covers more recent drought sequences (up to 2020).
- Series 3 uses the 10,000-year paleo-stochastic climate series without adjustment to undertake quality assurance (QA) against other scenarios. The purpose of this data is to show long-term climate variability in minimum inflows without the impact of climate change. This will be used for the purpose of identifying bias in model outputs compared to observational data (1895-2020) and for establishing a level of confidence in the climate adjusted scenarios.

Overall, the Panel finds that DCCEEW's approach of using paleo-stochastic data with a 10,000-year record to estimate minimum inflows is an improvement for incorporating the broader range of plausible historical climate information into minimum inflow estimates compared to using only the historically observed data prior to the commencement of the first WSP. Incorporating a broader range of climate variability – including that related to more severe low flows – begins to address the concerns over using flow information held prior to recent droughts and allows for explicit assessment of the risk of shortfalls to high security users. The Panel supports DCCEEW's underlying paleo-stochastic approach and encourages an adaptive approach to making improvements to data components.

## 3.1 Paleo-stochastic climate data

DCCEEW first developed the paleo-stochastic dataset to support the development of 13 regional water strategies to plan and manage water needs in NSW over the next 20-40 years (NSW DPE, 2023b). The paleo-stochastic datasets are used as inputs to DCCEEW's water models to support strategic water planning in NSW and assess risks to water availability. They are also used in the development of approaches to incorporate climate simulations to inform revisions to the estimation of minimum inflows (discussed in Section 4.1.1).

The paleo-stochastic dataset simulates 10,000 years of daily climate data produced using a stochastic model calibrated to instrumental historical climate data at key climate stations (e.g. rainfall stations) and paleoclimate data (e.g. tree rings, cave deposits, coral and ice cores). Observational rainfall and temperature data date back to the 1890s, and evaporation data date back to the 1970s[12]. These data are used as inputs into rainfall runoff and river system models (Figure 2, Appendix 2).

The paleo-stochastic climatic sequences are randomly generated by a probability model that preserves observed statistics including seasonal mean, standard deviations and serial correlation on an annual scale (a measure of how wet or dry a year is based on whether the previous year was wet or dry). This improves the representation of extreme events in the stochastically generated record. In

[10] *Water Sharing Plan for the NSW Border Rivers Regulated River Water Sources 2021*, for an example

[11] *Water Sharing Plan for the Belubula Regulated River Water Source 2012*

[12] The draft Method does not differentiate between evaporation, evapotranspiration, and potential evapotranspiration for this dataset.

addition, a stochastic Interdecadal Pacific Oscillation (IPO)[13] signal is integrated into the model, which intensifies the wet and dry extremes of the stochastic record. This is because paleoclimate records indicate that wet and dry cycles also appeared in the pre-observational record and are strongly related to positive and negative values of the IPO.

In 2020, this paleo-stochastic climate dataset and its implementation were reviewed by an independent expert panel convened by OCSE in the context of reviewing the climate risk method for the NSW Regional Water Strategies (RWS) Program (OCSE, 2020). This report focused on the development of stochastic models informed by knowledge of dominant climate drivers affecting different regions of NSW. Characteristics of these drivers were then used to inform understanding of the historical statistical nature of rainfall and ET.

One of the key findings of the OCSE 2020 Review was that the paleo-stochastic climate data generation approach was fit for the purpose of long-term analysis of impact for strategic planning purposes (i.e. assessing long-term water security options). While the paleo-stochastic climate data has previously been used in the development of RWS, the present review focuses on how the data can be used to inform revisions to the minimum inflow estimates underlying the allocations process (covered in Chapter 5). Elements of the OCSE 2020 Review are appropriate for discussion in the present Review.

The use of paleo-stochastic datasets provides information on plausible natural long-term climate variability, such as length and severity of historical droughts (including occurrences which were more severe than those in the 1890-2020 instrumental record). By combining multi-decadal, annual, seasonal and daily distributions of rainfall and potential evapotranspiration (PET) at multiple climate sites, the 10,000 years of daily data produced by coverage of key climate stations can be used to model all inland river systems in NSW and most of the coastal draining river systems. The 10,000-year paleo-stochastic dataset provides a broader range of plausible historical climate conditions to inform the estimation of minimum inflows. However, it is important to note that the paleo-stochastic dataset calibrated to historical climate data does not provide any information about future climate change impacts on minimum inflows, as these data assume climate stationarity (NSW DPE, 2023b).

## 3.2 Suitability and quality of stochastic climate data

The suitability of the stochastic climate dataset to inform the estimation of minimum inflows requires validation against the observed record to ensure that the paleo-stochastic climate represents reasonable climate characteristics. Assessment of the quality of the climate data was undertaken as part of generation of the dataset[14] and reviewed in the OCSE 2020 Review.

The use of the stochastic climate data in each modelling stage, including both the rainfall-runoff and hydrological model components, is also able to be validated. The suitability and quality of the stochastic climate data in being used to simulate runoff will be evaluated against runoff simulations using historical observed data. DCCEEW identified that they would evaluate statistical characteristics compared with runoff generated using the instrumental record. In cases where discrepancies in statistical characteristics are deemed too high, DCCEEW will qualitatively interpret the results, taking any bias into account. The draft method did not provided details outlining the approach taken in evaluating these statistics, determining whether biases are unacceptable or how biases will be considered.

The QA method for the stochastic data used in the minimum inflows project selects time series replicates from the stochastic set data that are the same length as the instrumental period. For

[13] An IPO is a natural climate pattern in the Pacific Ocean that causes variations in sea surface temperatures over decadal timescales (10-20 years)

[14] Available at https://datasets.seed.nsw.gov.au/dataset/water-modelling-stochastic-climate-data/resource/data_quality_report/pdf

example, the Border Rivers currently have a 134-year instrumental period, so the replicates selected from the 10,000 years of paleo-stochastic data are also 134 years. For each replicate, the 'stochastic distribution' is calculated based on the statistics or metrics of interest. DCCEEW advised that metrics that describe management outcomes (e.g. water allocations for different licence types) and management-relevant statistics (e.g. storage behaviour) are favoured over those that describe general climate conditions (Appendix 3). Because differences in time series length have been accounted for, it is possible for DCCEEW to compare and evaluate the stochastic distribution against observed statistics. The statistic calculated for each stochastic replicate may be very different from the instrumental metric, because of inherent randomness. However, the expectation is that the stochastic distribution consistently contains the instrumental statistic.

The Panel is comfortable with the suitability and quality of DCCEEW's approach to using paleo-stochastic climate data to inform minimum inflow determinations and endorses using the quality assurance/quality control (QA/QC) processes and techniques developed by DCCEEW to validate the suitability of the stochastic climate dataset against management-relevant metrics (Appendix 3).

### 3.2.1 Climate non-stationarity

There is an implicit assumption that historical climate patterns will persist into the future if only historical instrumental data is used to inform future water management decision-making. This assumption of climate stationarity fails to account for observed and expected future changes in climate (Milly et al., 2008). Given the extensive evidence that the climate is changing, the Panel recommended in the OCSE 2020 Review that "[the Department] engages external expertise to undertake a two-step approach to investigate stationarity over the historical record to ensure that models do not underestimate current and hence future climate risk" (OCSE, 2020). Following this recommendation, DCCEEW undertook non-stationarity tests in the northern and southern Murray-Darling Basin (Devanand et al., 2024a; Devanand et al., 2024b)

The methodology for the approach in the southern Basin was reviewed by OCSE in the 2021 Review, *Additional advice subsequent to April 2020 Panel report – Southern Inland NSW and Greater Sydney Region* (OCSE, 2021). The non-stationarity tests found a statistically significant increasing temperature trend in the northern inland Murray-Darling Basin (Devanand et al., 2024b) and statistically significant increases in temperature and decreases in cool season rainfall in the southern inland Murray-Darling Basin (Devanand et al., 2024a). Based on these findings, temperature changes have been incorporated into the climate data used in the minimum inflows draft Method in the northern Basin, with further consideration to be given to rainfall changes in the southern Basin.

### 3.2.2 Use of Interdecadal Pacific Oscillation (IPO)

It is difficult to know whether water users are in an IPO positive or negative cycle when making decisions on AWDs based on the current climate. The stochastic approach embeds low frequency variability by generating a stochastic sequence of IPO phases, which helps with understanding how it may be possible to adapt AWDs to climate change signals in streamflows that are highly uncertain. The stochastic data is informed by a paleoclimate stochastic sequence of IPO positive and negative phases, which introduces an element of persistence. At this point in time, DCCEEW is not proposing to use subsampling of the paleoclimate record based on the current setting of the IPO to assess risk.

The Panel finds that the long-term risk can be reasonably characterised using the paleo-stochastic data. However, the short-term risk of the period of an AWD (i.e. a year) is where conditional sampling could be useful. The Panel recommends further investigation into whether sampling of the paleo-stochastic data, conditional on current IPO state, would lead to different estimates of minimum inflows than those made using the full 10,000-year record.

## 3.3 Rainfall runoff models

### 3.3.1 Impact of vegetation responses

The Panel finds DCCEEW's approach to the generation of paleo-stochastic climate data to be satisfactory. However, in the long run, the approach may oversimplify climate change by only focusing on changes in atmospheric climate data, and not climate change impacts on landscape and vegetation. For example, the impact of vegetation responses to increasing atmospheric carbon dioxide ($CO_2$) concentrations on the hydrologic cycle could be considered in the rainfall runoff modelling that is forced by the paleo-stochastic data (Robertson et al., 2024).

The probability that a heavy rainfall event falls on a drier catchment is increasing. This is because the warmer atmosphere and warmer soils allow vegetation to grow for more days a year, which means more transpiration – which then dries the soil profile. The effects of this can be seen in the 'greening' of catchments inferred using remotely sensed vegetation indices that act as proxies for leaf area index (OCSE, 2021). Increasing leaf area index reflects embedded carbon and may result in higher ET. If ET increases, then the partition between so-called 'green' and 'blue' water changes and there are therefore changes for runoff, which have implications for water users. Additionally, extreme rainfalls are increasing whereas annual rainfall is decreasing, potentially leading to more dry days (Ukkola et al., 2015; Rifai et al., 2022).

Therefore, irrespective of stationarity in the meteorology, the ability of a catchment to absorb water is increasing and thereby reducing catchment yields. For catchments depending on smaller events, this could have a large impact. In the OCSE 2021 Review, the rainfall runoff models by DPIE Water (former DCCEEW Water Group) did not incorporate vegetation response – as expressed by canopy conductance (GC) and leaf area index (LAI) – which respond to climate forcing and environmental stress (OCSE, 2021). While this poses challenges for all rainfall runoff models, not just those used by DCCEEW, it is an area where improvements are warranted.

DCCEEW's approach could be improved by the inclusion of additional climate factors besides rainfall and temperature. This would have to be accompanied by an understanding and documentation of how vegetation can be incorporated into rainfall runoff models. At present, the rainfall runoff models do not model vegetation, so any changes in the vegetation processes cannot be represented. This is a clear barrier to being able to model all the sources of non-stationarity affecting runoff. While it is important to represent these changes, the Panel understands that DCCEEW is constrained by both what can be modelled operationally and uncertainty in the direction of rainfall changes in the future. This is an area where improvements will have to be implemented over time and DCCEEW should sponsor work in this area to adapt their rainfall runoff models where appropriate.

### 3.3.2 Rainfall runoff model calibration

Traditionally, rainfall runoff models are calibrated and then assessed on an independent period (split sampling) to determine their accuracy in streamflow simulations versus observations. Split sampling was not used in the calibration of DCCEEW's rainfall runoff models. Models will perform more poorly under drier conditions if they are calibrated under wetter conditions. However, models that are calibrated under dry conditions have a smaller performance loss if they are used under wet conditions. Shorter calibrations may be less robust than using the full data period and so split sampling may not be the best approach (Arsenault et al., 2018). Rainfall runoff models have very few parameters and the risk of overfitting them is small. Best practice guidelines from eWater Source[15] do not recommend either approach (Vaze et al., 2012). Shen (2022) also questions the use of split sampling as best practice and suggests that the most robust split sample decision is to calibrate to

[15] The eWater Toolkit is a publicly owned platform that provides a suite of water and catchment management tools used by DCCEEW. eWater Guidelines for water management modelling are available here: https://toolkit.ewater.org.au/Tools/Best%20Practice%20Modelling%20Guidelines/documentation

the full available data and skip model validation entirely (Shen et al., 2022). DCCEEW have noted that calibrating over the full period, using a good quality optimiser, trained on an appropriate range of objective functions, provides the most robust outcome for their models.

The Panel's support for DCCEEW's approach is contingent on the assumption of long-term stationarity, however in the context of climate change, where stationarity is not given, the role of split sample testing could be considered. Split sample testing can also be used to evaluate whether a rainfall runoff model can simulate non-stationarity in streamflow. For instance, $CO_2$ fertilisation may lead to increased vegetation greening and potentially greater ET. Conversely, water use efficiency may also increase and hence ET may not change. Regardless, if a rainfall runoff model does not account for this, it may still overestimate future runoff. Split sample testing may serve as a diagnostic tool to identify such shortcomings although it has been shown that split sample testing may still underestimate the impacts of climate non-stationarity on rainfall runoff modelling (Stephens et al., 2020). Ultimately, while stochastic models simulate climate variables such as rainfall and temperature, streamflow is also influenced by vegetation dynamics, which are themselves affected by climate change. Therefore, it is important to adopt a holistic perspective when considering the effects of non-stationarity in the draft Method.

# 4. Climate change data

To incorporate near-future climate information into the estimation of minimum inflows, the draft Method proposes scaling the 10,000-year paleo-stochastic climate sequence (described in Section 2) with parameters derived from NARCliM simulations to generate two time series (Series 4 and Series 5). Series 5 represents a ‘stress test’ scenario (to 2050).

NARCliM is based on regional downscaling of Coupled Model Intercomparison 6 (CMIP) Global Climate Models (GCMs). Projections are based on the Shared Socioeconomic Pathways (SSPs) emissions scenarios established by the Intergovernmental Panel on Climate Change. The NARCliM 2.0 projections have been gradually released throughout 2024 and 2025. Emissions scenarios were therefore incorporated into each Series pending data availability at the time DCCEEW wrote the draft Method. NARCliM 1.0 is proposed to be used for the southern connected Basin (Murrumbidgee and Murray regulated river water sources) due to perceived challenges with obtaining access to hydrological models required to incorporate the more recently updated NARCliM 2.0 in these areas. NARCliM 2.0 projections tend to be hotter and drier than NARCliM 1.0/1.5, so Series 5 may have lower climate variability in the southern connected Basin. While this isn’t ideal, it still provides some basis for factoring climate change into the estimation of minimum inflows. The Panel suggests that the differences in NARCliM 1.0 and 2.0 data for these catchments are investigated in more detail to better quantify the risk of using older climate datasets, at least in the short term.

While there is room for improvement in the draft Method for estimating minimum inflows, and limited information has been provided on inputs and assumptions of data, the Panel finds the core approach to incorporating climate change information into estimates of minimum inflows to be an improvement over current practice.

## 4.1 Series 4: Operational Scenario

Series 4 represents near-term climate change impacts. Series 4 uses 10,000-year paleo-stochastic data scaled for increased PET, driven primarily by increased temperatures, as a best-estimate scenario of climate conditions over the life of the WSP (i.e. to up around 2035). The Panel notes that there is relative certainty that PET will increase. Rainfall is not scaled as there is less certainty around how rainfall will change with projected climate change over the near-term (e.g. uncertainty in the direction of change), as described in section 3.1.1.

### 4.1.1 Adjustment of stochastic evapotranspiration

At the time the draft Method was presented to the Panel, DCCEEW proposed using the NARCliM high emissions scenario (SSP3-7.0) to develop seasonal scaling factors (given as per cent increase per season) specific to individual valleys, noting that emissions scenarios will be updated as additional modelling becomes available.[16] NARCliM scaling factors will be centred on 2035 and will be used to derive regional, seasonal Morton’s Wet Area Potential Evapotranspiration (Mwet) scaling factors using maximum and minimum temperatures, specific humidity, air pressure and incoming solar radiation. The seasonal scaling factors will be applied to the existing paleo-stochastic time series for each valley to generate a 10,000-year time series that is used to inform the estimation of minimum inflows.

For the next 10-year cycle of the WSP for the Border Rivers, DCCEEW is planning to scale the 10,000-year time series (Series 3) based on changes in PET to reflect the significant temperature trend identified in instrumental data. In the case of rainfall, no significant trend was identified and the

[16] In the final Review stages, SSP2-4.5 ensemble means became available. DCCEEW has therefore stated that they may use SSP2-4.5 ensemble means for Series 4 to be consistent with Series 5 in the final version of the Method.

time series will not be scaled. The rationale for scaling by PET only is based on a report assessing non-stationarity for stochastic time series generation in the northern Basin (Devanand et al., 2024b). This report found no statistically significant climate signal for streamflow changes in the northern Basin, indicating that variations in rainfall in the north are still attributed to natural variability in climate. Until the mechanisms of non-stationarity for NSW catchments are understood, it is a reasonable compromise to run Series 4 based on an increase in PET if there is consideration that a 10-year update plan for WSP will incorporate new knowledge as it emerges.

Given there is relative certainty that PET will increase over time, and that we are already experiencing elevated temperatures, adjusting PET by scaling temperature in the 10,000-year record is a priority to understand impacts on estimates of minimum inflows. It is the Panel's view that using Series 4 allows for better representation of current climate than observed data or stochastic data representing historical climate (i.e. Series 1-3). Adjusted PET stochastic data should be the baseline case to inform estimates of minimum inflows rather than unadjusted stochastic data, as proposed in the draft Method.

Further clarification around the use of ET (actual) versus PET (potential) in the draft Method is required. The documentation for the draft Method (both the draft Method itself and the supporting documents) switches between using ET and PET. In the context of this project, everywhere that ET is used can be read as PET. In terms of best practice, it would be better for documentation to be consistently explicit that PET is being discussed, particularly in the context of climate change and the previous OCSE reviews.

The Panel recommends DCCEEW improve clarity in terminology, as highlighted in the OCSE 2020 Review (Recommendation 3.1). Despite acceptance and completion of this recommendation, the current draft Method still lacks clarity, particularly around ET, PET and the terms 'baseline' versus 'base case'.

### 4.1.2 Emissions scenario selection

The NARCliM 2.0 data for the low (SSP1-2.6) and high (SSP3-7.0) emissions scenarios were recently published, and while data for the medium emissions scenario (SSP2-4.5) was expected in early 2025, it had not yet been released at the time that DCCEEW wrote the draft Method. In their proposed approach, DCCEEW advised scaling the 10,000-year paleo-stochastic climate sequence using either the low or high emissions scenario, or the medium scenario pending data availability. The Panel notes that the selection of SSP3-7.0 over SSP1-2.6 or SSP2-4.5 may not ultimately impact the near-term PET scaling approach because the divergence in each scenario's annual average temperature is narrower over the near term. An analysis of the scaling factors for each scenario could provide transparency on the scale of differences arising from scenario selection.

### 4.1.3 Adaptive management with release of new data

NARCliM 2.0 offers improvements compared to previous versions of NARCliM, such as updated climate models and finer spatial resolution (4 km across south-eastern Australia, versus 10 km in NARCliM 1.0 and 1.5). NARCliM is based on a subset of CMIP6 GCMs that have been dynamically downscaled using a Regional Climate Model (RCM). The GCMs simulate a range of plausible future climate conditions over the planet for extended periods of time using varied greenhouse gas emissions scenarios, while the RCM is forced by GCM data to simulate climate information at a scale that is more relevant for water management.

The OCSE 2020 Review recommended that the (then) DPIE-Water "begins the process of planning to incorporate NARCliM 1.5 into calculations (to incorporate climate change into stochastic data sets)" and work with a "community of practice to explore incorporation of NARCliM 2.0" (OCSE, 2020). DCCEEW has implemented both recommendations, as reflected in the draft Method approach to scaling paleo-stochastic data with NARCliM climate change series and detailed in Appendix 5.

An adaptive management strategy could incorporate specific triggers to prompt a review of the estimation of minimum inflows in response to changing conditions outside those anticipated in the draft Method. For example, a plan suspension or receiving minimum inflows below the modelled range might trigger an earlier review. The development of newer climate models with higher levels of confidence or statistical evidence of climate change impacts (such as detection and attribution type studies) could be used as indicators for a review. This approach would allow for more adaptive and responsive management and is supported by the Panel. Integrating climate change information, a broader range of climate variability and real-time data into the determination of the minimum inflows improves the representation of a broader range of plausible minimum inflow conditions to inform water management.

## 4.2 Series 5: 'Stress Test' Scenario

The Series 5 dataset represents a 'stress test' scenario. DCCEEW has noted this terminology will be updated to 'trajectory' upon completion of the final Method. It is centred on the year 2050 and uses scaled rainfall data as well as PET to adjust 10,000-year paleo-stochastic data. The rainfall data will be scaled monthly for each valley based on a multi-model mean, whereas the PET scaling will be scaled as per Series 4.

DCCEEW originally intended to use SSP3-7.0 for Series 5, but at the time of the draft Methods the option became available to use the SSP2-4.5 scenario. The purpose of the stress test is to inform an adaptive pathway and provide an indication of where estimates of minimum inflows may be heading beyond 2035, however the output of Series 5 will not be directly used to inform AWD decision-making in the next 10 years.

The Panel's comments for emissions scenario selection deviate from the advice for Series 4 modelling, as 2050 is further into the future so there is more difference in the radiative forcing between the SSPs and there is less agreement in the models. The difference is likely to be more evident in the southern valleys. The Panel therefore supports DCCEEW's adaptive approach to incorporate updated data as it becomes available and re-evaluate their methodology.

The draft Method selects the year 2050 for Series 5 as an appropriate time scale to inform an adaptive pathway and provide stakeholders with an indication of potential future changes without reaching so far into the future that uncertainty significantly increases. The data in Series 5 equates to a global temperature increase of 2.0°C over pre-industrial levels by 2050[17]. However, as 2024 was confirmed to be the warmest year on record globally, with the average global temperature > 1.5°C over pre-industrial levels (C3S, n.d.), the time frame over which the stress test is relevant will likely require regular updating. Given the current rate of global warming, it is possible that Series 5 will be more applicable for informing an adaptive 'next step' over the near term (e.g. 10 years) versus informing an adaptive 'pathway' until 2050.

### 4.2.1 Definition of 'stress testing' and risk communication

The Panel notes that while the Series 5 'stress testing' approach appears technically robust, the potential effectiveness of its application to inform estimates of minimum inflows beyond 2035 is not clear (discussed in Section 5.1.3). There is discrepancy between models including wide ensemble ranges of projected change in average rainfall in NARCliM projections resulting in high levels of uncertainty.

Using Series 5 adjusted for different 2050 states informs possibilities, but with the vast variability in the impacts across the pathways, it is difficult to propose any use for Series 5 that is more

[17] For more information, see the NARCliM website: www.climatechange.environment.nsw.gov.au/projections-map.

practicable than “wait and see”. Clear communication and framing of the considerable uncertainty over future risks with Series 5 stress testing is a critical element of this work. There is a clear need to define the decisions that can and will be informed by the stress testing simulations.

Careful communication is needed to ensure users understand that the ‘stress test’ or ‘trajectory’ provides some insights about potential future minimum inflows but does not define a certain set trajectory (further detail in section 5.1.3). The Panel also does not consider it appropriate to describe this Series as a ‘worst case’ scenario. While it may represent the worst case of the scenarios evaluated, it does not represent the commonly used understanding of a worst case due to uncertainties in modelling assumptions and lack of information around climate non-stationarities.

Additionally, the Panel advises clarity on the timing and mechanism for reviewing the draft Method, especially regarding the stress test component. The time frame for the stress test scenario will also need to be adaptive. In 10 years, 2050 will be approaching the 10-year WSP planning horizon and a new stress test time frame will need to be chosen.

### 4.2.2 Climate change scaling parameters

The draft Method does not clearly define how the climate scaling will be applied to the paleo-stochastic time series. It is unclear if the full ensemble of NARCliM models will be used to derive the scaling values or if a single model will be used. If only mean scaling was to be applied, the multi-model ensemble could be used to calculate the scaling values. However, this would not allow for changes in rainfall extremes that may differ from changes in the mean (e.g. extreme rainfalls are expected to increase even if models project overall drier conditions).

It is recommended that daily quantile scaling for each month be applied. This would require the scaling factors to be calculated for each NARCliM simulation, as the multi-model ensemble average reduces the magnitude of changes at the daily temporal scale. This may require trade-offs in the number of NARCliM RCMs that are used for the analyses. Best practice for precipitation data would be a daily quantile scaling approach using each of the 10 NARCliM models separately (5 GCMs and 2 RCMs; 5 x 2 = 10) to provide 10 sets of scaling factors to be applied to the 10,000 years to give 10 x 10,000 years. If it is computationally difficult to run more than one paleo-stochastic scenario, it may be necessary to pick a subset of NARCliM simulations to use for the stress test.

For PET, the draft Method indicates that seasonal scaling will be used. The Panel considers that monthly scaling is a more reasonable approach, given the concepts of seasons are relatively arbitrary. The distribution of daily PET is less skewed than precipitation and the direction of change for the mean is almost certainly the same as for higher quantiles, so applying mean scaling over monthly time scales will not lead to a loss of future variability.

**Recommendation 1: Prioritise short- to medium-term improvements to the Method including climate datasets, rainfall runoff models and adaptive management**

> **Recommendation 1.1 (short term):** Increase the level of detail in the Method describing climate data and modelling, inputs, assumptions, and determining biases of data and how they will be considered. This information should be included in relevant documents in the initial or first version. Subsequent iterations to the Method for estimating minimum inflows should be published as discrete versions, as opposed to as an evolving draft within the broader Minimum Inflows Project. The Method should contain enough technical and scientific detail to be reproducible.
>
> **Recommendation 1.2 (immediate and ongoing):** Identify possible sources of systemic, compounding bias by validating modelled data against instrumental data, with a particular focus on model performance over extended periods of low flow. Publish information and methods taken to address biases. If observed conditions fall outside a pre-identified

range, a review of the Method should be triggered to determine causes of the discrepancy and potential improvements.

**Recommendation 1.3 (short term):** Given that the concept of seasons is arbitrary, PET in Series 4 & 5, and PET and rainfall in Series 5 should be scaled using monthly factors to ensure that future changes in variability are not excluded in the scenario.

**Recommendation 1.4 (medium term):** Investigate whether sampling of the paleo-stochastic data, conditional on IPO state, will lead to different short-term estimates of minimum inflow than those made using the full 10,000-year record.

# 5. Operationalising climate risk into AWD decision-making

This chapter focuses on the suitability of the draft Method for determining minimum inflows for the purpose of operationalising climate risk into AWD decision-making (TOR 1). The estimated minimum inflows sit as one of several data components included in the AWD decision-making process. The Panel notes that other components of the AWD decision-making process – such as data around demands and losses – are outside the scope of this Review. The Panel also notes that the draft Method proposes significant changes in AWD decision-making processes (potentially requiring changes to policy and legislation) which are outside the scope of this Review.

The Panel considers that applying the revised minimum inflow methods to the current AWD decision-making framework would be an appropriate means for operationalising climate risk into the minimum inflow component informing the AWD process. However, the Panel notes that operationalising climate risk into AWD decision-making requires further modifications to other inputs that feed into the AWD process. Other changes to the AWD decision-making process would be highly effective in operationalising climate risk but are outside the scope of this Review.

Overall, if applied within the existing AWD decision-making process, the draft Method would improve on significant limitations of the current approach for estimating minimum inflow sequences, particularly those related to the use of historical instrumental data and explicitly excluding the Millenium and Tinderbox Droughts. While evidence-based improvements could be made to the draft Method, it represents a strong conceptual framework that takes the first critical step towards providing information on climate variability and potential climate change impacts on estimates of minimum inflows that form part of the AWD decision-making process.

## 5.1 Technical commentary

### 5.1.1 Adequacy of river system models for informing AWD decision-making

River system models are generally built to model the rules of the WSP and to demonstrate compliance with that plan. The models have been peer reviewed and are generally considered suitable for their intended purpose, which is to assess the bulk hydrological mass balance under a repeat of historical climatic conditions. However, they are not specifically calibrated for drought operations, and it is unclear if the models are fit for purpose for informing system behaviour in low flow conditions. There are recognised limitations in the performance of the current models in representing low flow conditions which are simulated with varying degrees of skilfulness.

While not the predominant focus of this Review, the Panel found through reviewing the draft Methods that there is an opportunity for DCCEEW to update model calibrations and validation approaches (of both rainfall-runoff models and river system models) to focus on low flow metrics and improve representation of the model process representing river operations, demands, losses and user behaviour during dry and drought periods.

Given the importance of representing low flow conditions in the models to evaluate drought responses for towns, water users and the environment, DCCEEW could consider the development of improved or additional purpose-specific model configurations. These configurations should be calibrated and validated specifically for improved representation of low flow conditions, for use in the draft Method and for other analyses related to dry and drought conditions. There should also be ongoing evaluation of the sensitivity of the model outputs against underlying assumptions and model configurations used. One key area requiring improved evaluation is the demand assumptions, where there is generally no representation of reduced town water use during dry and drought periods.

### 5.1.2 Conditional inflow and return period tables

The current method for estimating minimum inflow involves calculating the accumulated inflow over historical records and identifying the lowest volume that occurs during a defined time window, generally two years or less. However, DCCEEW intends to revise this approach using updated data from the 10,000-year climate datasets. DCCEEW proposes using the climate-adjusted paleo-stochastic datasets to compile inflow volumes associated with a range of return periods (or frequencies). The inflows associated with each return period will be applied within a series of monthly water balance calculations based on assumed fixed priority demands (including PEW provisions) and fixed losses to identify the minimum volume reached in the headwater storage for each return period and duration. The Panel is only able to comment on the use of the draft Method to compile inflow volumes associated with a range of return periods, as demands and losses determining storage reserves are outside the scope of this Review.

The tables are a simplistic way to clearly collate and summarise a significant amount of hydrological data in a way that is accessible to decision-makers. One benefit of using the tables is that there is no absolute need to define a specific duration. In practice, an acceptable level of risk could be chosen and used to define the lowest inflow volume indicated along that line of risk. That inflow volume will likely then be at or above the defined acceptable risk level for all durations (up to 72 months). Ultimately, determining the risk level still lies with the decision-maker, which is a matter of policy and therefore outside the scope of this review. The Panel is of the view that the use of the tables to determine a range of minimum inflow estimates represents an interim solution that improves on the previous approach and moves towards a more risk-based approach. This view is conditional on fair and transparent communication of an adopted risk level and its implications for priority water users.

## 5.2 Implementation and decision-making

Appropriate consideration of climate change information into AWD decision-making involves consideration of data, methods and policy which are outside the scope of this review. While the Panel is comfortable that DCCEEW's draft Method will provide improved insight into the likely effects of climate change on estimates of minimum inflows, how this information gets operationalised into AWD decision-making is also outside of the scope of this review.

WSPs currently require rivers to be operated to provide priority needs during a repeat of the worst drought on record, observed before the inaugural WSP. In practice this means guaranteeing supply for priority needs, generally over a two-year period, in the context of any drought occurring before 2004.

The proposed approach for incorporating updated estimates of minimum inflows into the AWD decision-making process changes this paradigm by moving to a risk-based approach which is inherently discretionary. In this context, decision-makers could be provided with climate-adjusted minimum inflow data and still choose a level of risk when determining storage reserves that doesn't accurately reflect potential future climate conditions nor different perspectives on an acceptable level of risk. This situation could potentially lead to over- (or under-) allocation of water, with adverse consequences for water users and/or the environment.

As the approach is not finalised, and risk determinations have not yet been made, DCCEEW was unable to provide any evaluation of the proposed approach over significant historical climate events, including the Millenium and Tinderbox droughts. Therefore, there is no evidence available as to the effectiveness of the revised approach or any improvements/limitations of the approach in managing water sharing during recently experienced drought periods.

### 5.2.1 Incorporating climate change information into minimum inflows

The Panel believe that DCCEEW should move away from the current method used to calculate minimum inflows as a component of the AWD process to take advantage of the available stochastic data (as proposed in the draft Method). The Panel also consider that it would be appropriate to operationalise the use of the revised minimum inflows within the current AWD method. However, DCCEEW is proposing significant revisions to the AWD decision-making process which are outside of the scope of this review, and so the Panel is not able to comment on the use of revised minimum inflows in DCCEEW's proposed approach.

The Panel notes that while incorporating climate change information related to minimum inflows is a critical first step in improving AWD processes, equally important is the improved incorporation of climate change information related to losses, changes in usage, population growth and resultant potential increases in town water supply entitlements, to reduce the risk to delivery of essential needs, all of which are outside the scope of this Review.

### 5.2.2 Understanding uncertainties and model bias

Uncertainty in climate change modelling can emerge from several sources, including uncertainty in parameters and datasets (e.g. inputs into the model). These can introduce uncertainty about the probability of future events and can have considerable influence on uncertainty in water yield, a concept that has dominated urban water resource planning. Challenges include attributing interdecadal or interannual variability to an underlying change in climate when it is possible that there were simply wet or dry years.

Uncertainty also introduces an additional concern about the possibility of systemic, compounding bias which could ultimately misrepresent the resultant risk profile and/or the impact on other water uses, including the environment. To address these concerns, the Panel recommends validating modelled data against instrumental data. In practice, observed inflows can be compared against a range of modelling outputs through a multiple-lines-of-evidence approach. If observed conditions fall outside of a pre-identified range, a review of the draft Method should be triggered to determine causes of the discrepancy and potential methodological improvements.

While DCCEEW’s draft Method is a step in the right direction, it needs to be clearly communicated to decision-makers that the rainfall runoff model and its outputs are not a forecast. Instead, they can be used to simulate outcomes based on a series of assumptions such as climate change-adjusted temperature and precipitation. The rainfall runoff models are not able to provide specific outcomes on the effects of climate change and how it will impact minimum inflows. Instead, the models and their outputs simply inform an adaptively managed process where, when managed well, minimum inflows estimates used in the AWD decision-making process can adjust to a changing climate.

### 5.2.3 Evolving methodology

The process for how the minimum inflows draft Method will provide data that can operationalise climate risk into AWD decision-making is still evolving, and major components of the AWD process are outside the scope of this Review, making it challenging for the Panel to review. Climate change is a dynamic, ongoing process and therefore processes incorporating climate change into all elements underpinning water management require regular revision and iterative improvements. The NSW Government should fund and convene a standing Expert Panel or other consulting body responsible for providing expert input to the ongoing review of DCCEEW's AWD decision-making process and the data informing it (e.g. minimum inflows). This Panel should consist of professionals with relevant expertise, be independent of DCCEEW and the Water Group, and operate in an advisory capacity to ensure that evidence-based guidance informs decision-making on a continuous basis.

Adaptive management should be used to ensure that the methods for the data that feed into AWD decision-making processes are revised when improved information around how to effectively manage the uncertainties of climate change is available. Triggers for process adjustments, timeframes for incorporating new data and adjustments to overall AWD decision-making will need to be implemented through a continuous review approach that should be clearly communicated to stakeholders. The inherent uncertainty of climate change and continued improvement in climate model approaches requires regular updates to water management approaches to continue to incorporate improved information. Therefore, triggers for review should be set to detect changes in metrics that are outside a defined range (i.e. changes larger than what should be possible in the short term or have been observed historically).

Access to independent advice on ongoing modelling improvements will also ensure that an iterative and adaptive management approach is maintained beyond this Review. For example, the Panel could advise on how to implement the proposed approach across basins to consider each valley’s unique characteristics, how the approach informs risk, and how it can be implemented into water allocation processes on an ongoing basis.

Panel members could include risk-based environmental professionals, irrigators and other experts who have experience in applying the draft Method. This would assist DCCEEW to work through challenges involved in addressing climate change in estimates of minimum inflows and broader AWD processes, providing technical oversight of adjustments to the method during implementation.

A model example is the Advisory Committee on Tunnel Air Quality (ACTAQ). ACTAQ consists of a range of experts/officers across government and academia undertaking work to better understand air quality issues associated with road tunnels in Sydney (OCSE, n.d.). ACTAQ undertakes regular studies and produces technical reports as part of ongoing advice to government on issues that arise from the assessment and operation of road tunnels. ACTAQ also provides advice to the appropriate Department on air quality aspects of relevant Environmental Impact Statements, which is then published on the Department's Major Projects Assessment portal. Transparency and/or oversight of this decision-making is important for ensuring that stakeholders have confidence that modelling has been applied robustly.

**Recommendation 2: Adaptively manage the Method for estimating minimum inflows. Continue to refine the Method over the longer term by establishing a framework that is adaptively updated as new information becomes available**

**Recommendation 2.1 (ongoing):** Ensure the Method is considered an adaptive framework. Set trigger points that prompt adjustments to the estimation of minimum inflows, such as plan suspensions or minimum inflows below the modelled range. Update data underpinning minimum inflows with relevant climate-scaled paleo-stochastic data as newer NARCLiM versions become available.

**Recommendation 2.2 (long term):** Incorporate changes into rainfall runoff models for the surrounding landscape and vegetation affected by increasing atmospheric carbon dioxide ($CO_2$).

**Recommendation 2.3 (short term and ongoing):** Convene a standing Expert Panel to advise on the ongoing revision of processes related to estimating minimum inflows and their incorporation into AWD decision-making processes. This Panel should consist of professionals with relevant expertise, be independent of DCCEEW and the Water Group, and operate in an advisory capacity to ensure that evidence-based guidance informs decision-making on a continuous basis. This panel could also provide ad hoc advice on specific technical aspects of the Methods as needed, particularly when applying them across different valleys.

**Recommendation 2.4 (long term):** The NSW Government should provide a long-term commitment through appropriate resourcing to DCCEEW's efforts to ensure an adaptive approach to the incorporation of climate change into water management practices in NSW.

**Recommendation 2.5 (short term and ongoing):** Use multiple lines of evidence to continue to inform estimates of minimum inflows by finding the most suitable data using both model outputs and return period table outputs and clearly defining confidence intervals for both.

### 5.2.4 Transparent communication

DCCEEW should provide clear and transparent communications related to the draft Method. This is particularly important for clearly delineating changes proposed to the approach to estimating minimum inflows from any other policy changes related to AWD decision-making under consideration. Poor communication risks undermining the robust science within the draft Method and community trust in both the draft Method and the decision-making process.

Clear and transparent communication is especially important in this complex multi-faceted project. Addressing the risks of climate change and water security requires complying with legislative requirements in water sharing to protect the water source and its dependent ecosystems and basic landholder rights, coupled with diverse stakeholder perspectives. This can result in overwhelming amounts of information, a lack of common understanding and, ultimately, lack of stakeholder support. The Panel notes the progress made on the ‘community of practice’, which was a recommendation (number 10) in the OCSE 2020 Review (OCSE, 2020), and suggests this level of open communication with stakeholders continues. Communicating the full breadth of uncertainty and adopting an adaptive planning approach that integrates uncertainty into decision-making will allow many water users to make planning decisions in response to a changing climate.

**Recommendation 3: Improve transparency on methodological details around terminology and scenario usage and provide clear communication to decision-makers and stakeholders**

**Recommendation 3.1 (short term):** Clearly communicate to decision-makers that the estimates of minimum inflows are not a forecast but rather form an adaptively managed process which can provide guidance for adjusting AWD decision-making to reflect a changing climate.

**Recommendation 3.2 (short term):** Use explicit terminology and language in the Method to improve clarity. For example, documentation should be consistent and explicit that the Method uses PET in the rainfall runoff modelling.

**Recommendation 3.3 (short term):** Prioritise effective communication and framing of uncertainty with Series 5 ‘stress testing’ and make outputs public so that stakeholders are adequately informed of proposed changes to minimum inflow estimates.

**Recommendation 3.4 (long term):** Provide greater transparency around the work undertaken to operationalise climate risk in minimum inflows in the AWD decision-making process to build stakeholder trust and confidence.

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# Appendices

Appendix 1: Terms of Reference
Appendix 2: Draft technical review method
Appendix 3: Validating climate risk data for use in Border Rivers water sharing
Appendix 4: List of documents provided to the Panel by DCCEEW for consideration in the Review
Appendix 5: Department updates from 2020 OCSE Review

## Appendix 1: Terms of Reference

# Minimum Inflows Method Review – Terms of Reference

**Background**

The Minister for Water, the Hon Rose Jackson MLC, requested the Office of the Chief Scientist & Engineer (OCSE) to convene an independent expert panel to review a draft method to review the minimum inflows used in making available water determinations (AWDs) in regulated water sources.

Water in government-owned storages in regulated river systems is distributed via an AWD process governed by the *Water Management Act 2000, Water Management (General) Regulation 2018* and provisions specified in relevant water sharing plans (WSPs). The process conducted for AWDs is implemented by the Water Group in the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) with support from WaterNSW and documented in protocol documents published by DCCEEW. The AWD process uses an accounting method to reserve an amount of water to secure supply to high priority water users, and to share the volume above this reserve to other water users.

In quantifying the amount of water expected to be available, WSPs require the water supply system to be operated in such a way that water would be able to be supplied during a repeat of the period of lowest accumulated inflows to the water source, to meet priority requirements for basic landholder rights, domestic and stock, local water utility and high security access licences. Current WSPs specify the period of lowest accumulated inflows to the water source as identified by flow information held by DCCEEW on a particular date. For example, the WSP for the *NSW Border Rivers Regulated River Water Source 2021* states *"flow information held by the Department prior to 1 July 2009".* This period of 'lowest accumulated inflows' is also known as the 'minimum inflow' sequence.

Nine inland regulated river WSPs include a provision requiring review of their periods of minimum inflows. Refer to Attachment A for a list of plans which include this review provision.

These review provisions are a follow-up to a commitment in the NSW State Water Strategy (Action 4.2) to "*Review water allocation and water sharing in response to new climate information*". DCCEEW has since made a commitment as an outcome of settling a legal action to have the Office of the Chief Scientist & Engineer (OCSE) undertake an independent expert review of the method.

DCCEEW has developed stochastic climate datasets which incorporate paleoclimate evidence and allow consideration of projected climate change impacts. The approach to developing these datasets was reviewed by an independent panel chaired by the OCSE in 2020 (Independent review of the climate risk method for the NSW Regional Water Strategies Program Independent Expert Panel 2 April 2020). This review found that the climate datasets were fit for purpose and a significant advance on relying on historical data alone.

DCCEEW is developing a method which uses these datasets to review the 'period of lowest accumulated inflows', with the assessments informing necessary changes to the accounting process for conducting AWDs. This method will be developed and initially trialed in two regulated river water sources – the NSW Border Rivers and Murrumbidgee. A sample of WSP requirements for this review is included in its entirety in Appendix A for reference.

DCCEEW is seeking advice on the suitability of the method for its purpose of operationalising climate risk into AWD decision making.

**Scope**

*The OCSE will convene a technical panel with relevant experts to address the following:*

1. Review the suitability of the minimum inflows methodology for its purpose of operationalising climate risk into AWD decision making.
2. On the basis of climate data quality assurance outcomes, review the suitability of the stochastic datasets used in the methodology that feeds into the broader AWD process.
3. Review the suitability of DCCEEW's approach to incorporate climate change into the methods described in TOR 1 & 2.
4. Provide recommendations for improvements to DCCEEW's methods that can be applied in the short and medium term.
5. Provide recommendations on any other matters the panel considers relevant.

Note: The Method is the process of using stochastic datasets, adjusted for climate change, to determine high security reserve storage for different risk levels. The selection of risk level of security for high priority water users, including consequent impacts on other water users and planned environmental water in regulated systems across NSW is outside of scope and is therefore not subject to comment by the Panel.

**Out of Scope**

- Review of DCCEEW's river system models of the regulated river water sources used for these assessments.
- Review of other aspects of the AWD method, including the calculation of losses and reviewing entitlement volumes.
- Recommendations on an appropriate level of risk to water user.

**Proposed requirements**

A panel of recognised experts in the subject of the review will be convened to review the method used by DCCEEW to incorporate climate risk into the analysis underpinning minimum inflow assumptions in available water determinations. The panel will be chaired by the Deputy Chief Scientist & Engineer, and panel members should collectively hold significant experience in climate variability and change, water management, and risk assessment.

**Final Advice**

The OCSE will produce a report to the Minister and DCCEEW setting out their findings and recommendations on the Terms of Reference. It will be made publicly available on the OCSE website. Final report to Minister April 2025 (TBC).

**Attachment A**

NSW Water sharing plans with provision for review of 'Maintenance of water supply' clause.

| Water sharing plan | Minimum flows review required date |
|---|---|
| **Water Sharing Plan for the NSW Border Rivers Regulated River Water Source 2021** | 2 July 2026 |
| **Water Sharing Plan for the Murrumbidgee Regulated River Water Source 2016** | 30 June 2026 |
| **Water Sharing Plan for the New South Wales Murray and Lower Darling Regulated Rivers Water Sources 2016** | 30 June 2026 |
| **Water Sharing Plan for the Gwydir Regulated River Water Source 2016** | 30 June 2026 |
| **Water Sharing Plan for the Lachlan Regulated River Water Source 2016** | 30 June 2026 |
| **Water Sharing Plan for the Macquarie and Cudgegong Regulated Rivers Water Source 2016** | 30 June 2026 |
| **Water Sharing Plan for the Belubula Regulated River Water Source 2012** | 30 June 2026 |
| **Water Sharing Plan for the Upper and Lower Namoi Regulated River Water Sources 2016** | 30 June 2026 |

An amendment to the Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016 is in progress that will add the review provision, with the review required by 30 June 2026.

## Appendix 2: Draft technical review method

Department of Climate Change, Energy, the Environment and Water

# Technical review method

## Minimum inflows review

October 2024

OFFICIAL

# Acknowledgement of Country

The Department of Climate Change, Energy, the Environment and Water acknowledges the traditional custodians of the land and pays respect to Elders past, present and future.

We recognise Australian Aboriginal and Torres Strait Islander peoples' unique cultural and spiritual relationships to place and their rich contributions to society.

Artist and designer Nikita Ridgeway, from Aboriginal design agency Boss Lady Creative Designs, created the People and Community symbol.

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Technical review method

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## More information

[Click here to add lines to identify author, unit, location, and any other information. DELETE THIS SECTION IF NOT NEEDED]

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# Contents

# 1 Introduction

This document describes the method the Water Group in the New South Wales Department of Climate Change, Energy the Environment and Water (the department) will use to review minimum inflows. Minimum inflows are currently used to determine water availability in NSW regulated river water sources through a process that determines the storage reserves needed to provide water security to the environment and high priority water users.

The current minimum inflows review has two main drivers:

1. regulatory requirements in regulated river water sharing plans to review how minimum inflows are defined
2. Action 4.2 of the NSW Water Strategy which commits the department to *review water allocation and water sharing in response to new climate information*

The review also reflects a commitment to address the issue as part of the settlement of *Nature Conservation Council of New South Wales v Minister for Water, Property and Housing* in relation to its consideration of climate change in the Border Rivers Regulated Water Sharing Plan. This includes a commitment to have the NSW Office of the Chief Scientist and Engineer convene an independent panel to review the minimum inflows project's draft method.

Further information can be found in the Background section of the document.

## 1.1 Minimum inflows project scope

The scope of the minimum inflows project is governed by the project requirements outlined above and consists of four main components:

1. a review of elements in the water allocation process, particularly the assumptions relating to expected inflows, and a consideration of amendments that could incorporate climate change and provide a clearer understanding of water supply risk
2. an impact assessment using scenario modelling that focuses on water balance, environmental and economic assessments
3. an options analysis
4. stakeholder engagement over shortlisted options.

The interaction between these project components is shown in Figure 1. This review method document covers the first component only and does not consider the impact assessment methods, options analysis or stakeholder engagement methods. The current document also does not include a review of methods to amend water sharing plans.



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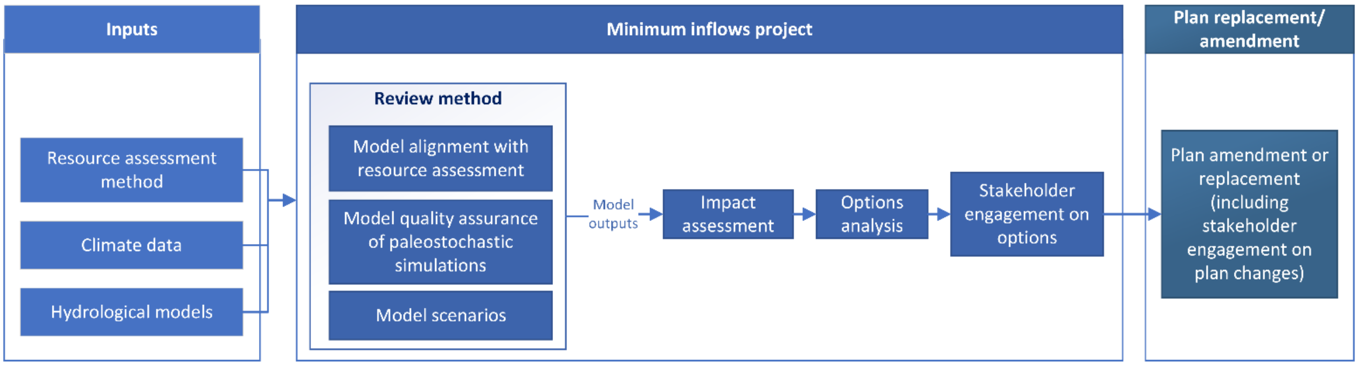


Figure 1. Minimum inflows review scope and component interaction

## 1.2 Document outline

Chapter 2 of this document provides background information on water sharing plans and the general process for allocating water in NSW regulated rivers. This chapter also describes how minimum inflow sequences and storage reserves are currently estimated . Limitations of the current methodology and potential methods to overcome these limitations are discussed. Chapter 2 also provides an overview of our existing hydrological and river system models and the climate datasets used to drive them, including the ways in which climate change risks are typically explored using these datasets and models.

Chapter 3 presents the proposed methods for the three interlinked components of this minimum inflows review: the available water determination (AWD) process, the use of extended stochastic climate sequences in models in representing water allocation, and the use of model scenarios to investigate the potential effects of climate change on water allocation and water security from alternate inflow sequences or storage reserves.



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# 2 Background

## 2.1 Water sharing plans and the available water determination process

The *Water Management Act 2000* (the Act) is the primary piece of legislation governing the use of water from surface water environments and groundwater systems across NSW. The management of individual water sources is regulated through water sharing plans, which are statutory instruments established under the Act.

The Act sets out water management principles (s 5) and establishes water licence categories (s 57). Other key functions of the Act regarding the allocation of water include:

- determining the relative priority of each licence type (s 58), with the highest priority given to high priority requirements, including basic landholder rights, domestic and stock requirements and town water supply.
- providing for the preparation of water sharing plans, which prescribe the water sharing rules for each water source and allocation of water to licence categories in priority order
- providing for the allocation of water through available water determinations (AWDs; s 59)

Water sharing plans set out, in detail, how water is to be shared between consumptive users and the environment and how it is to be shared among the consumptive users of a particular water source or group of connected water sources. Valley-specific AWD-based allocation processes are detailed on the department's website. These are referenced for Border Rivers and Murrumbidgee at NSW DPE (2020a) and NSW DPE (2020b) respectively.

### 2.1.1 Water provisions for high priority users and essential supplies

Water sharing plans for regulated rivers include a provision that requires that enough water be reserved to meet high priority requirements during a repeat of the 'period of lowest accumulated inflows'. Inflows during this period defines the 'minimum inflow' and serves as a baseline describing a conservatively low total volume of water expected to enter the system. The length of the minimum inflow sequence determines the planning horizon, and reserves are held to meet high priority requirements over that planning horizon.

The water sharing plans stipulate that the minimum inflow sequence for each regulated river system is determined using flow information that was held by the department prior to the start of the first water sharing plan for that river system. For most of the inland regulated water sharing plans this date is 1 July 2004. In the NSW Border Rivers, Peel and Belubula it is 2009, 2010 and 2012 respectively.

The lowest accumulated inflow data are drawn from departmental water models. The inflows represented in these models are based on observed flows at stream gauges upstream of the storage. The data at these stations were extended and filled as required through back calculation of inflows and hydrologic modelling of ungauged catchments.

Methods to calibrate headwater inflows and storage inflows are described in Australian Modelling Practice notes collaboratively developed by the department's and other national and state government water management agency modelling groups. Further description of methods are contained in other practice notes prepared for the Australian Modelling Practice; in published model build reports (NSW DPIE 2020a)with and an overview available in presentations prepared for stakeholder engagement (NSW DPE 2021a, 2021b, 2022a, 2022b).

### What is considered high priority requirements?

The water sharing plan details relevant high priority requirements in the maintenance of supply clauses. These include:

- Basic landholder rights
- Domestic and stock licences
- Local water utility licences
- Major utility licences
- High security licences
- Conveyance licences
- Environmental water allowances
- Replenishment flow volumes
- End of system flows
- Operational requirements such as transmission losses, evaporation, dead storage

## 2.1.2 Management of severe droughts

Water provisions through the AWD process are not the only tool for managing water allocation in extreme conditions. If predicted inflows do not eventuate, a drought response may be triggered.

For water sharing plans the Extreme Events Policy (NSW DPE 2023a) establishes the principles by which all regulated river water resources will be managed during an extreme event such as a drought or sudden deterioration in water quality. This policy aims to ensure critical human water needs are met and gives effect to the water sharing priorities under s 60 of the Act.

The policy framework establishes a staged approach and provides a range of measures that water managers can deploy as conditions deteriorate. In the case of a severe drought, the management response involves progressively introducing more stringent measures to support the highest priority needs as the event becomes more critical. Incident Response Guides (IRGs) required by the Basin Plan provide further detail on possible actions during drought and water quality events.

## 2.1.3 Review provisions for determining the lowest accumulated inflows

Since 2004, there have been more severe droughts, with the Millennium (2001 – 2009) and Tinderbox (2017-2020) droughts each causing record low inflows into most water storages and triggered the implementation of the Extreme Events Policy. This caused uncertainty for high priority water users and generated community concern that the current allocation process and minimum inflow sequence does not consider the plausible impacts of climate change.

Most of the regulated river water sharing plans include a provision that requires a review of options for defining the period of lowest accumulated inflows. The review provision includes requirements to determine the impact of any options on planned environmental water (PEW) and other access licences and to consider the views of stakeholders and the broader community.

Work is underway for the remaining regulated river water sharing plans to be amended to include the provision. The text of this review provision from the *Water Sharing Plan for the NSW Border Rivers Regulated Water Source 2021* is reproduced in Appendix 1.



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### 2.1.4 The NSW Water Strategy

The NSW Water Strategy (NSW DPIE 2021c) sets the strategic direction for water management in NSW and commits to climate change action. Priority 4 of the strategy aims to increase resilience to potential changes in water availability due to variability and climate change.

Action 4.2 of the NSW Water Strategy is 'Review water allocation and water sharing in response to new climate information'. As set out in the Implementation Plan for the strategy, the department will initially test scenarios for water availability and allocations based on climate risk modelling scenarios in a pilot and then expand application to other valleys.

## 2.2 Current water allocation method

### 2.2.1 Allocation process for regulated rivers

In regulated rivers, the volume of water allocated to licence holders varies from year to year based on the licence category. Opening allocations are made at the beginning of the water year[1] on 1 July, with allocation to relevant planned environmental water requirements, domestic and stock licences, local water utility and major utility licences prioritised as prescribed in s 59 Once allocations are made for these highest priority licences, allocation begins for high security and then general security licences. Water cannot be allocated to lower priority licences until high priority requirements are fully met in accordance with the water sharing plan.

The amount of water available to allocate depends on including water in storage, account water carried over from the previous water year, water needed to meet high priority requirements, the volume required to run the river (operational requirements), and minimum inflows expected.

Resource assessments are periodically conducted throughout the water year to determine whether additional water can be allocated, for example, after there have been inflows significantly in excess of minimum inflows.

Figure 2 provides an overview of this process.

[1] The water year is the period 1 July to 30 June the following year

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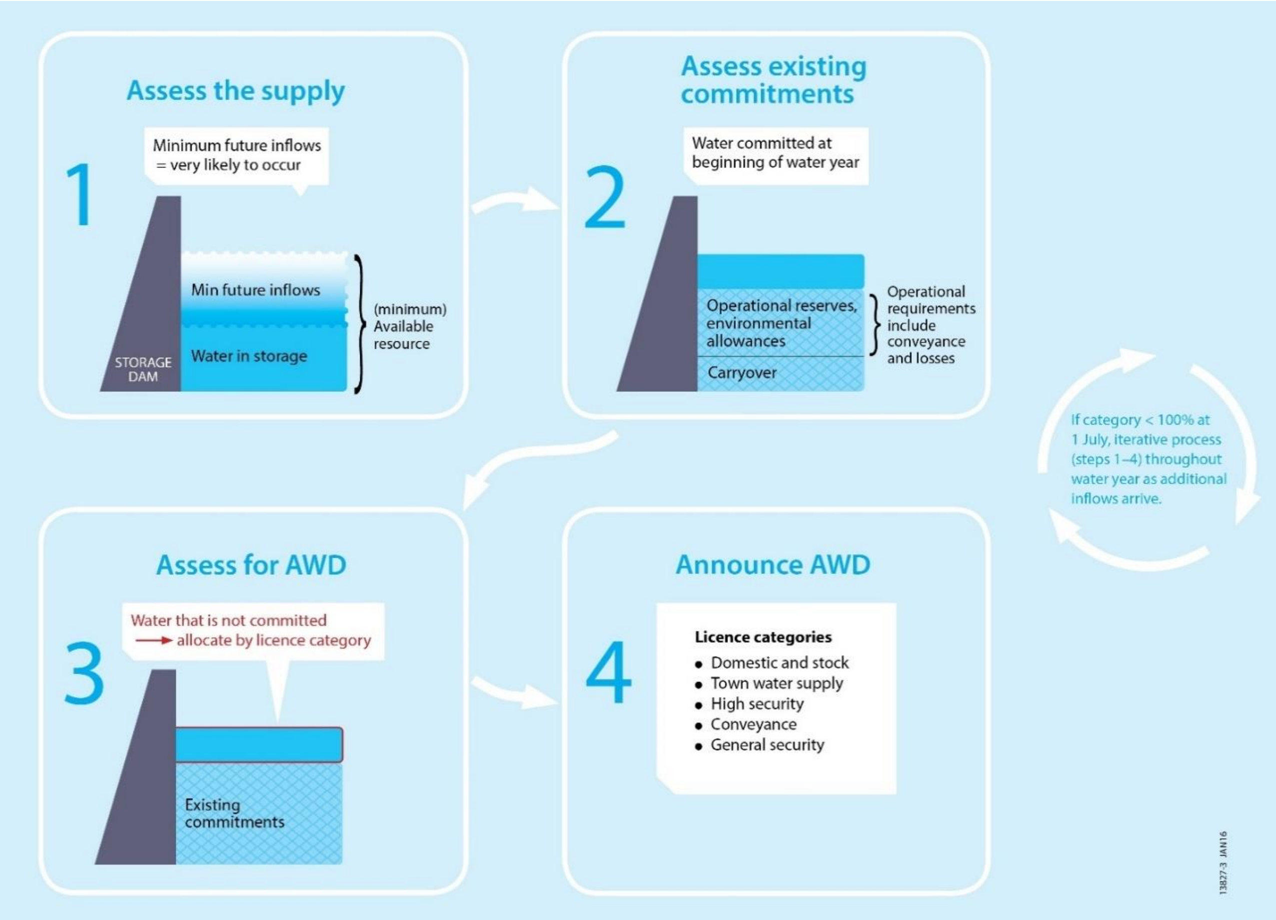


Figure 2. Water allocation process at beginning of the water year

### 2.2.2 Relationship between the storage reserve and minimum inflows

The storage reserve is a volume of water set aside in the storage to meet high priority requirements and operational requirements, offset by the expected minimum inflows. The volume of the necessary storage reserve in any given year is calculated using the following formula:

$$storage\ reserve = (high\ priority\ requirements + operational\ requirements) - minimum\ inflows$$

Thus, the expected minimum inflow volume directly affects the size of the storage reserve. For example, if the high priority requirements and operational requirements are a combined 200 GL and the expected minimum inflows are 110 GL/y, then the storage reserve is 90 GL.

Because of this relationship, any change in the way minimum inflows are determined will result in changes to the calculated storage reserve. These changes in storage reserve may in turn affect AWDs, general security diversions and the water security of high priority users (Figure 3). The respective direction of change in response to change in minimum inflows is shown by (+/-).

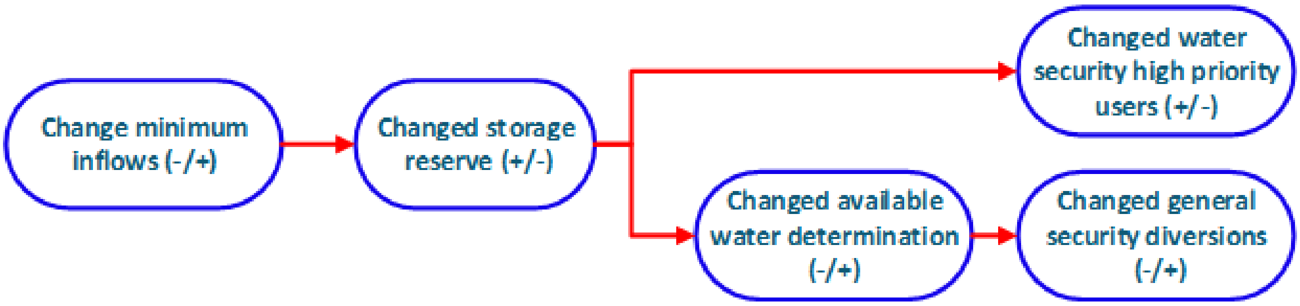


Figure 3. Relationship between minimum inflows, storage reserve, risk level and allocations

### 2.2.3 Limitations of the current approach

There are a number of limitations associated with the minimum inflows and storage reserve aspects of the available water determination process, including:

- reliance on a set climatic period to define the storage reserve (past droughts may not reflect future droughts)
- not accounting for improvements in modelling and hydrological analysis tools that could enable them to identify different minimum inflow sequences, especially outside the window for which observational data is available.
- a lack of well-understood water security expectations for high security and essential supplies water users, e.g., how often they would expect to see inflows lower than the minimum inflows specified in the water sharing plans.
- The current AWD process allows for discretion in estimating some components.

#### 2.2.3.1 Recorded droughts may not reflect future droughts

The historical data used to determine the minimum inflow sequence is drawn from observed climate and flow records that started in the 1890s, yielding over approximately 130 years of observed data. These records prior to the first water sharing plans do not include observations made during the periods of new record low inflows that occurred during the Millennium Drought (2001–2009) and the Tinderbox Drought (2017–2020). These record low inflows resulted in the suspension of parts or all of water sharing plans and the need to manage for 'critical human needs', causing uncertainty for water users and issues with delivering water to towns.

Given these recent extreme events and the ongoing evidence of climate change impacts such as increased temperature being recorded in NSW, there is concern that water allocation methods based on historical data do not provide an appropriate level of security and certainty, particularly for high priority water users.

The assumption that estimated minimum inflows between the 1890s and 2000s form a sufficiently conservative baseline for the provision of water security to high priority water users has not been borne out by experience. There are lines of evidence in paleoclimate records, stochastic modelling and climate change scenario modelling suggesting that plausible future droughts could be even more severe.

Climate change is expected to have major impacts on rainfall, temperature and evaporation. Continuing with the status quo will increase uncertainty for all water users.

#### 2.2.3.2 Data improvement

The current water sharing plans stipulate the minimum inflow sequences as data held by the department prior to the start of the first water sharing plan. Subsequently, these datasets have been periodically updated based on additional data and better estimation methods to reflect a principle of continual improvement.

Examples of the source of improvements in pre-first water sharing plan estimates derive from

- Headwater inflow rainfall runoff-model calibration methods that were previously manually calibrated are now calibrated using optimisation software,
- Methods to estimate ungauged catchment inflows and associated 'losses' as part of reach calibration steps have been refined and codified.
- Additional gauged data during more recent dry periods has become available which has provided an improved data set to calibrate against.

Methods to calibrate headwater inflows and storage inflows are described in Australian Modelling Practice notes collaboratively developed by the department's and other national and state government water management agency modelling groups.

As a result of these enhanced methods and additional data, and ongoing improvement in our modelling practice, the minimum inflows stipulated in the water sharing plans may not necessarily represent the best currently available estimate of inflows prior to the first water sharing plan.

Further, the inflows used in the plans are based solely on instrumental climate data. The enhanced paleo-stochastic data sets provide a greater sample size of possible climate data inclusive of more extreme dry conditions leading to lower minimum inflow sequences.

## 2.3 Hydrological and river system models

The department has built and maintains daily time-step river system models for all of NSW's major river systems. These models are used to inform water management policies and planning, evaluate climate risks and monitor and report on how the department is meeting its legal obligations relating to limiting diversions, including water sharing plan provisions.

The models consist of a suite of daily time-step rainfall-runoff models calibrated to quality-assured flow data using rainfall and evaporation data. These calibrated models are then used to generate long-term river flows, which are inputs to river system models that simulate the water storage, allocation, delivery, diversion and streamflow processes.

The models were originally developed in an Integrated water Quantity and Quality simulation Model (IQQM) platform and are currently being progressively transitioned to the national hydrological modelling platform Source. Each river system model is independently reviewed for quality and effectiveness when it undergoes a major upgrade, such as the upgrade of the floodplain harvesting program in the northern basin or is rebuilt using Source.

The models represent the key natural and management-related processes and their interactions in an integrated software framework. Inputs to the models include spatial data, including stream networks and water infrastructure, and temporal data, including time-series flow and climate data.

The build and maintenance of the models follows a best-practice guidelines framework developed in collaboration with other water management agencies to ensure consistency and scientific robustness.

The river system models are updated annually with the prior water year's hydroclimate data for extraction compliance assessment and are periodically upgraded with new data and additional capability. The models are reviewed by independent experts following major upgrades. For example, the NSW Border Rivers model has been independently reviewed on 3 occasions (See Alluvium, 2020; Bewsher 2021; Fifteen50, 2022).

The department maintains scenario variants for models in each valley. The different scenarios may include incremental changes in configuration of model components, sensitivity analysis, changes in calibration over time, and levels of management and development. For statutory and stakeholder trust purposes, particularly diversion compliance and assessing changes for statutory plans, the department recognises the importance of justifying the selection of reference model scenarios.

The department has prepared transparent guidelines for this purpose (NSW DCCEEW, 2023a; 2023b), which has multiple criteria such as existence of documentation, independent reviews, currency of data. These guidelines developed for LTAAEL compliance are relevant for model selection to assess change resulting from this minimum inflows review.

### 2.3.1 Model limitations and assumptions during extreme drought

The department's daily time-step models have been used since the mid-1990s to determine water availability, flows and diversions under varying climate conditions. Their outputs inform and support contemporary water management decisions, such as rule changes in water sharing plans, and to track annual and long-term diversion compliance.

Several design criteria were established to enable the models to meet their objectives. These included the ability to represent key physical and management processes, capture climate variability and water usage under a range of water availability conditions, report at multiple spatial and temporal scales, and allow further updating and extension as required. The objectives and design criteria are reported in more detail in the department's model build reports.[2] Each model build report contains a comprehensive description of the model's conceptualisation, data, calibration, assemblage and overall performance for a range of climate conditions.

As with all models, there are biases and uncertainties associated with the outputs. This is particularly the case during extreme conditions, for example when estimating transmission losses based on river operations. During periods of very low flows, river operations tend to be discretionary and governed by extreme event or drought response policies and frameworks, and more information is needed to better represent these conditions in models.

The valley specific reporting of results will provide an assessment of the impacts of this uncertainty on the outcomes of the modelling, and strategies and methods to mitigate these limitations.

## 2.4 Climate data availability for river system models

The department holds or has ongoing access to multiple sources of climatic data, including both observational climate data and modelled climate data. These data are used in catchment and river system modelling. The datasets and their generation are described briefly in the sections below, as they form the basis of the scenario modelling proposed for this project.

### 2.4.1 Instrumental data

Observational data, including rainfall and temperature data since the 1890s and evaporation data since the 1970s, are quality-assured and used by the department. These data are then used as inputs in all rainfall-runoff and river systems models.

### 2.4.2 Paleo-stochastic climate data

The department developed a paleoclimate-informed stochastic ('paleo-stochastic') climate dataset to support the development of 13 regional water strategies to plan and manage water

[2] For example, New South Wales Department of Planning, Industry and Environment (2020:4–5).





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needs in each NSW region over the next 20–40 years (NSW DPE 2023b). This dataset was used in the department's water models to comprehensively assess risks related to water availability.

The paleo-stochastic dataset contains 10,000 years of daily climate data produced using a stochastic model calibrated to instrumental data (e.g. rainfall stations) and paleoclimate data obtained from landscape features such as tree rings, cave deposits, coral and ice cores. This dataset provides a better understanding of natural long-term climate variability and the length and severity of droughts that occurred historically, providing a better estimation of climate risks to water security than using observed data only. The paleoclimate-informed dataset includes droughts more severe than those in the 1890–2020 record.

#### 2.4.2.1 Stochastic climate method

The method through which the paleo-stochastic climate data were generated in shown in Figure 4.

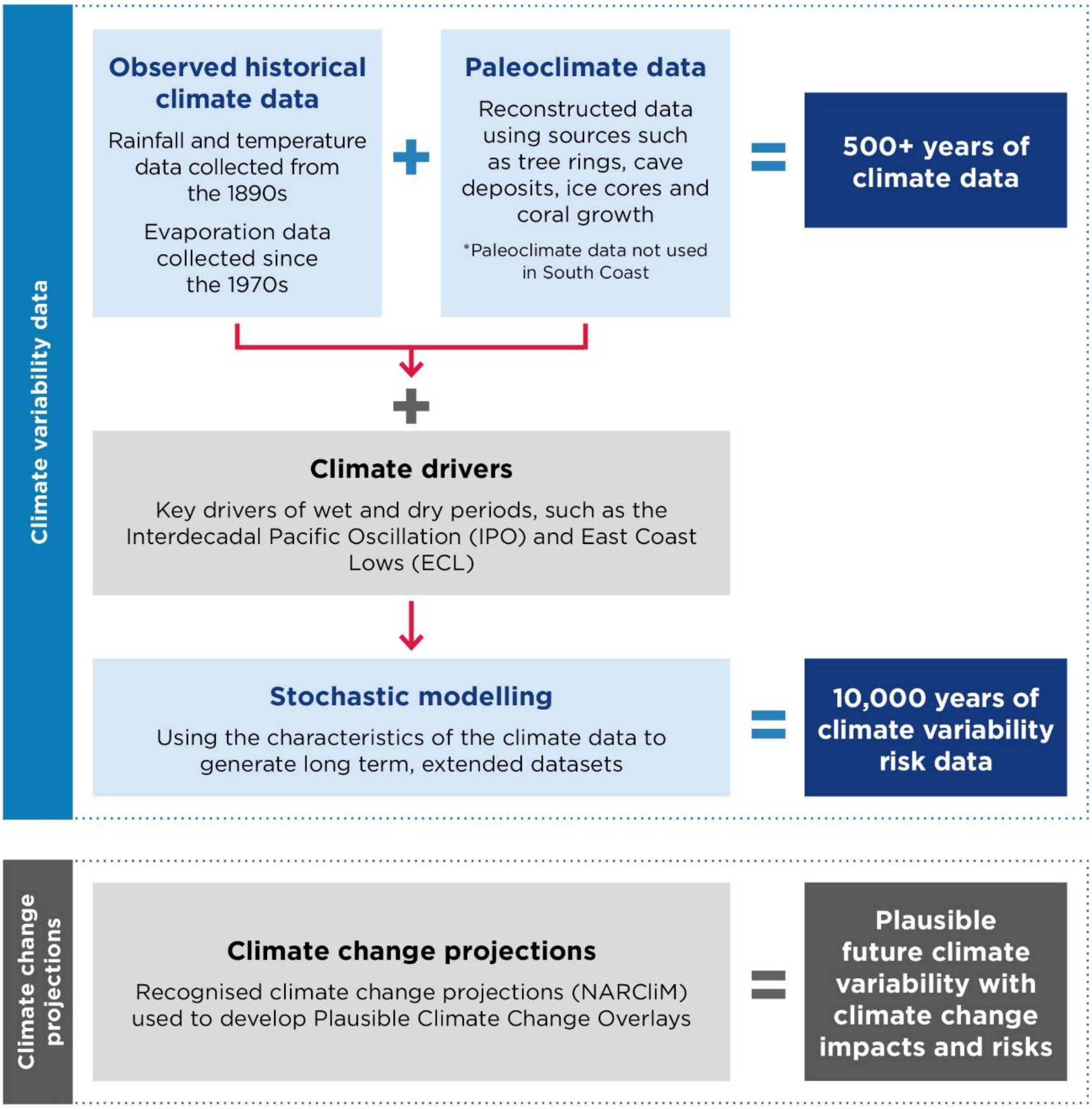


Figure 4. Approach to developing the paleo-stochastic climate dataset

The climatic sequences were generated based on statistics including seasonal mean and standard deviation values, random factors and serial correlation on an annual scale. Serial correlation, a measure of how wet or dry a year is based on whether the previous year was wet or dry, characterises the wet and dry clusters we see in observed records. Combining this characteristic with the random component creates more extreme events in the stochastically generated record.

The general stochastic generation process, which is based on the observational record alone, is enhanced when combined with paleoclimate data. For example, the observed record shows a very strong multi-decadal signal in the inland NSW climate, with the first half of the 20th century receiving about 10% less average annual rainfall than the second half of the 20th century.

Paleoclimate records indicate that these wet and dry cycles also appeared in the pre-observational record and were strongly related to positive and negative values of the Interdecadal Pacific Oscillation (IPO). A stochastic IPO signal was therefore integrated into the model, a step that intensified the wet and dry extremes in the stochastic record.

By combining multi-decadal, annual, seasonal and daily distributions of rainfall and potential evapotranspiration at multiple climate sites, the department produced 10,000 years of daily data with full spatial coverage of key climate stations. This dataset that can be used to model all inland river systems in NSW and most of the coastal draining river systems. A full description of this method is provided in NSW DPE (2023), with further technical detail in Leonard et al. (2019) and Leonard et al, .(2023b).

#### 2.4.2.2 Previous reviews of paleo-stochastic climate data

This paleo-stochastic climate data generation approach and its implementation were reviewed by an independent expert panel convened by the NSW Office of Chief Scientist and Engineer. The panel found the approach to be consistent with best practice and appropriate for use in strategic water planning (OSCE, 2020). The panel's findings took into account the department's combination of paleo-stochastic data with monthly change factors from the NSW and Australian Regional Climate Model (NARCliM).

The panel also recommended that the observational record be tested for 'climatic non-stationarity', or whether there have been trends or step changes in the climate, regardless of attribution. This was considered important in characterising the current climate and in making decisions about how to incorporate future climate change. Subsequent studies in response to that recommendation found a statistically significant increasing temperature trend in the northern inland Murray–Darling Basin (Devanand et al 2020a) and statistically significant increases in temperature and decreases in cool season rainfall in the southern inland Murray–Darling Basin (Devanand, et al, 2020b). As such, temperature changes will be incorporated into the climate data used in the minimum inflows project in the northern basin, with further consideration given to rainfall changes in southern basin.

### 2.4.3 Climate change-factored paleo-stochastic data

For regional water strategy applications, the results of the NARCliM 1.0 and 1.5 projects were used to factor the paleo-stochastic data. The NARCliM data are based on General Circulation Models (GCMs) that have been dynamically downscaled using Regional Climate Models (RCMs). These GCMs simulate climatic conditions over the whole planet for extended periods of time using a range of greenhouse gas emission scenarios.

For this review, the 10,000-year paleo-stochastic climate sequence will be scaled using NARCLiM 2.0. NARCLiM 2.0 offers improvements compared to previous versions of NARCliM, such as updated GCMs and finer spatial resolution. The NARCliM 2.0 data, which will include projections based on the Shared Socioeconomic Pathways (SSPs) emission scenarios defined by the Intergovernmental Panel on Climate Change, are being progressively released in 2024 and 2025. The results for low (SSP1–2.6) and high (SSP3–7.0) emissions scenarios have recently been released, and results for a medium emissions scenario (SSP2–4.5) will be available in early 2025.

Based on data availability, we could scale the 10,000-year paleo-stochastic climate sequence using either the low or high emissions scenario. To stress-test the AWD process, we selected the high emissions scenario. This is discussed further in section 3.3.2.

#### 2.4.3.1 Climate change-factored paleo-stochastic data for the southern connected basin

Ideally, for consistency, NARCliM 2.0 data would be used in reviews of the Murrumbidgee and Murray regulated river water sources. However, we are not in a position to do this in the short to medium term. Instead, our approach will be similar but not identical to that outlined above.

The Murrumbidgee and Murray models operate as water sources within the southern connected basin. Other water sources in that larger system include the Snowy Hydro Water system, which delivers water to the Murrumbidgee and Murray system, the Upper Murrumbidgee catchment, and the Victorian regulated and unregulated tributaries.

These models have been linked as part of the Murrumbidgee Regional Water Strategy project, which incorporates temporally consistent paleo-stochastic data and a dataset in which this paleo-stochastic data are factored by the driest NARCliM 1.0-modelled results.

Updating these model results would require renegotiating model access with other water agencies and conducting computationally intensive model updates within a modelling resource constrained environment. Neither of these issues are able to be resolved in the time frame of this project.

We expect the existing paleo-stochastic and NARCliM 1.0-factored paleo-stochastic results to be sufficient for the purposes of this review.

## 2.5 Chapter summary

In this chapter we have presented an overview of the current AWD process, the available hydrological models and the climate datasets used in these models. Datasets and models that will be available to the department for this minimum inflow review include:

- valley-specific catchment and river system models that simulate water storage inflow and the water allocation and delivery process according to water sharing plans
- instrumental data from the 1890s to present, currently used to build and calibrate hydrological and river system models for basin plan compliance purposes and to estimate the minimum inflow sequences that directly determine storage reserves
- paleo-stochastic climate data spanning 10,000 years for climate stations in the instrumental dataset
- NARCliM 2.0-factored paleo-stochastic data under the high emissions scenario SSP3–7.0 for climate stations in the instrumental dataset

This chapter also discussed some limitations of the models and methods used to evaluate the minimum inflow sequences used in the AWD process, including:

- the use of recent instrumental data as the only foundation for assumptions regarding minimum inflows and storage reserves
- the lack of information provided on the level of risk associated with the supply of high security water and essential supplies.

The availability of 10,000-year paleo-stochastic climate series data and series that factor for climate change provides an opportunity to investigate the limitations of the current storage reserve assumptions.

The following chapter describes how we intend to incorporate these datasets into the existing models and undertake the minimum inflow review by:

- demonstrating that the models reflect the current AWD process
- demonstrating that the AWD process in the models under 10,000-year paleo-stochastic inputs performs similarly to our current instrumental models
- modelling scenarios that test different AWD inflow and storage reserve assumptions and
- estimating the water supply risk associated with historic and potential future climates.

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# 3 Review Method

The proposed review method has three components:

1. an AWD review that assesses model alignment with the AWD process
2. quality assurance of stochastic simulations
3. testing of model scenarios and storage reserve assumptions under historic and plausible future climate variations.

The first two components of this review method are designed to provide supporting 'fit for purpose' information on the data and models used for this study.

By reviewing how the models currently align with the AWD process, the mechanisms through which the models estimate storage reserves will be compared to current operational practices. Verification of this alignment will provide confidence that the modelled allocation process reflects current practice and highlight how the model can be adjusted for the scenarios.

The quality assurance component compares instrumental model outputs specifically associated with water allocation with those generated from stochastic model runs. This step is designed to demonstrate that the stochastic simulations are robust and representative and therefore appropriate for testing scenarios that fall outside of the historic flow sequences that limit our current models.

The AWD and quality assurance components support the third step, which is using model scenarios to estimate changes to the water allocation system under different storage inflow assumptions and climate sequences.

## 3.1 AWD review

The AWD review is designed to investigate how well the model replicates the department's published AWD method. This AWD review will serve as an audit of both the allocation process and the model, ensuring that they both meet water sharing plan requirements and determining where changes are required to better align the two processes. The review will identify discrepancies and investigate their causes in a systematic way. This process is important in understanding the reliability and limitations of the modelling scenarios undertaken in the testing stage (section 3.3).

The AWD review will investigate the following elements in the AWD process:

- processes for the estimation of minimum inflows
- allowances for replenishment flows
- assumptions around release patterns of replenishment flows
- allowances for end-of-system flows
- allowances for losses due to evaporation, transmission and operations

The review will follow the method undertaken recently for the Macquarie and Cudgegong regulated river water source (NSW DPE 2023a).

The AWD review method is summarised below:

- obtain AWD decision history and associated worksheets used to make decisions
- audit a subset of AWD worksheets, comparing worksheet formulas, comments and assumptions to determine:



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  - consistency between worksheets
  - consistency with the appropriate water sharing plan.
- obtain the baseline river system model for the valley under review and the associated build report
- identify how the AWD process is modelled and how well this corresponds with the AWD worksheets
- compare modelled and observed allocations to identify any variances.
- investigate potential reasons for variances, such as how discretionary decisions are made, and consider whether this information could be included in the modelling method.

The outcome of the review will be a chapter in the valley report summarising the current AWD method, how the method is implemented in the model, the suitability or limitations of the model in replicating the current method and recommendations for any model amendments.

## 3.2 Quality assurance of stochastic simulations

Quality assurance was previously conducted on the stochastic data during its development by comparing the statistical distributions of key metrics of stochastic and instrumental climate and comparing the statistical properties of rainfall runoff modelled streamflow using stochastic and instrumental climate as inputs.

An additional stage of quality assurance has been designed specifically to assess the usage of stochastic climate data within the river system models (NSW DPE 2023b), both directly and in estimated inflows. This stage ensures that any potential biases in the climate data are known and can be factored into our assessment of the outcomes of this project.

The method for this additional stage involves comparing the results of model runs using instrumental data against those obtained from the 10,000-year paleo-stochastic model simulations. The same rainfall-runoff models and river system models are used for both sets of model runs, with only the climate and streamflow input sequences differing.

Four main areas describing the major water balance components have been chosen for the model output comparison:

1. storage inflows (24-month inflows and inflow exceedance and probability distribution), used to assess how the stochastic model inflows compare to the instrumental model inflows
2. storage behaviour (storage volume and exceedance of 5%, 10%, 20% and 50% full occurrence), used to assess how well the stochastic model represents critical storage thresholds compared to the instrumental model
3. extractions for high security, general security and supplementary water licences (exceedance curves, overall bias and skill score)
4. model mid-system and end-of-system flows, used to demonstrate similarities in simulated flow distribution

The quality assurance process produces plots for visual inspection and data tables.

For each model comparison category, we will produce:

1. a skill score based on the similarity of probability distributions (Perkins et al. 2007)
2. an absolute bias figure (%) of the modelled element
3. a p-value reflecting the probability that the two model outputs are consistent

4. an exceedance plot showing the instrumental model data, the median of the stochastic modelled data and a 95% confidence interval associated with the stochastic data.

An example of selected output from the quality assurance process is provided in Table 1 and Figure 5.

Table 1. Example of stochastic modelled results for the annual diversion performance metric

| Statistic | Skill score | Absolute bias (%) | % capture | p-value |
|---|---|---|---|---|
| General security annual extractions | 0.85 | 5.2 | 95 | 0.71 |
| High security annual extractions | 0.88 | 1.9 | 100 | 0.97 |
| Supplementary annual extractions | 0.84 | 6.8 | 85 | 0.71 |

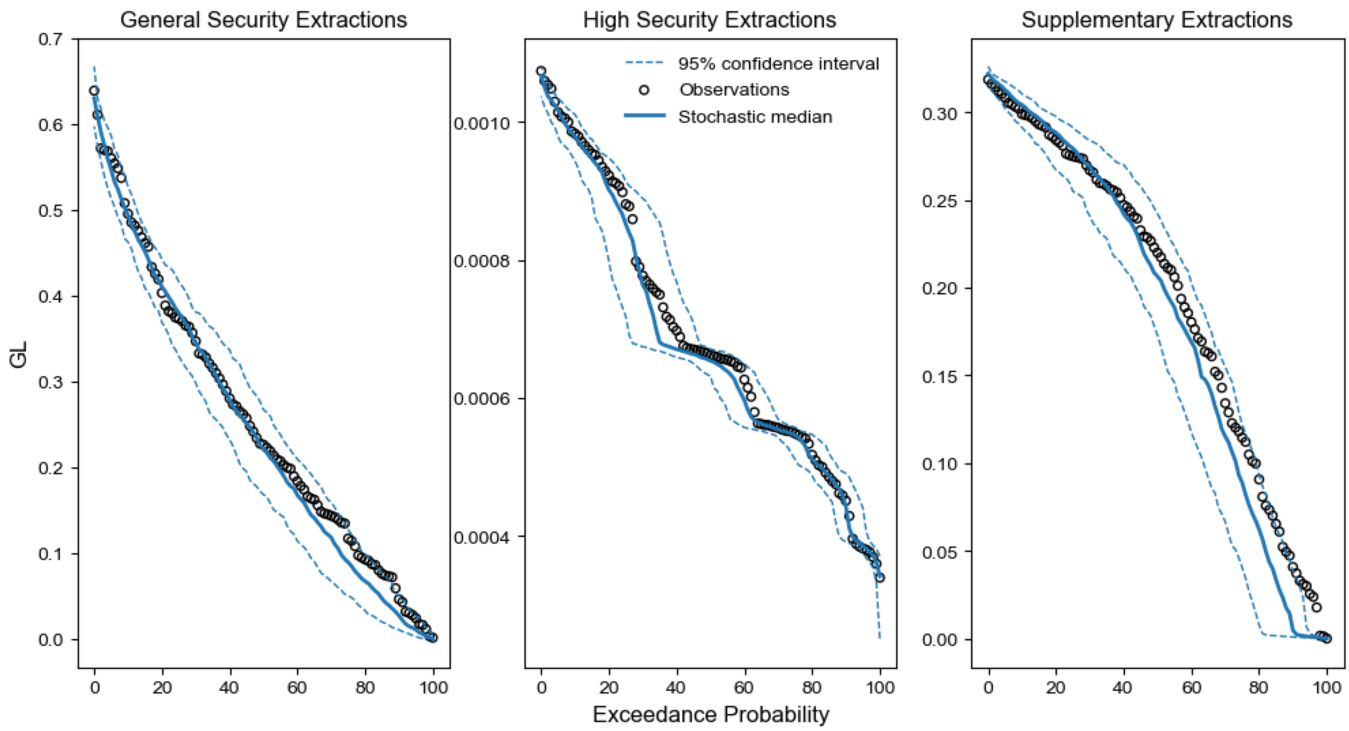


Figure 5. Modelled observed vs stochastic exceedance plots for high security, general security and supplementary access annual extractions

The outcome of the quality assurance step will be a series of graphs and data tables comparing the results of an instrumental model run with the results of a 10,000-year paleo-stochastic model run.

The data tables and plots will be inspected and the model given a fitness ranking to convey the overall confidence in using the 10,000-year paleo-stochastic model runs to assess water supply risks associated with the AWD process.

## 3.3 Testing of model scenarios and storage reserve assumptions under historic and future climate variations

The model scenarios proposed for this investigation are sets of models with different hydroclimate inputs along with varying the parameters associated with the storage reserve.

Chapter 2 highlighted the limitations of assessing water supply reliability by using minimum inflow sequences in historic instrumental datasets to calculate storage reserves for high priority water users. This chapter highlights the direct relationship between the minimum inflow sequence and the storage reserve volume.

Our proposed scenario modelling method will systematically vary the storage reserve and evaluate the resulting changes to water supply reliability. This is preferred to searching for and estimating the probability of minimum inflow sequences and defining model storage reserves based on these sequences. Our method does not presume a particular supply reliability target and instead models the range.

Using this method and modelling multiple storage reserves for a single climate series, we will develop supply reliability response curves that reflect changes in storage reserve volume under that climate scenario. We will do this separately for all climate series. We anticipate that these response curves will be sufficiently robust to allow some interpolation between points, allowing us to evaluate potential impacts to water supply for a given return period storages falling below critical supply thresholds.

Building on the enhanced expression of natural variability contained in the paleo-stochastic climate data developed by the department, this method has been chosen to account for limitations and risks with adopting a single projected climate change scenario as a substitute for the instrumental climate:

- while we understand that the climate is generally projected to be drier which will mean less flows, there is still a level of uncertainty to the extent of change. This makes it difficult to ‘choose’ a most appropriate projected climate change scenario and apply it to the current method given the validity of individual scenarios.
- Adopting a storage reserve based on the potential range of natural variability and projected climate change scenarios allows the department to be suitably conservative based on a risk-based scenario.
- The storage reserve method appears to be more adaptable. As we get a better understanding of the future climate, adjusting the storage reserve volume based on risk is a simpler and more transparent option that can readily be amended as we better understand plausible future climate conditions.

We anticipate that our daily time step river system models will be sufficiently robust to model water storage behaviour using different storage reserve assumptions under normal water sharing plan operational conditions for all hydroclimate conditions. When very dry inflow sequences occur, these models will indicate when and how often water storages will drop below specific critical storage levels. In such cases, models will not allocate water to general security water accounts and will be operating to only supply the essential requirements.

At some point during very dry sequences, water storages will drop to a point where water sharing plans may be suspended. This typically occurs before a storage reserve is depleted to the extent these critical requirements cannot be met. In such cases where water sharing plan suspension is likely, model assumptions surrounding the provision of essential supplies may no longer be robust. This is because river system models have been built and calibrated to represent water sharing plan conditions and not necessarily extreme cases where water sharing plans are suspended. In such cases, we anticipate that the models can still be used to indicate the likelihood of entering an essential supplies only phase, but not necessarily the storage behaviour whilst in this phase.

To provide some indication of storage behaviour whilst in an essential supplies phase, we propose to compile inflow volumes associated with a range of return periods from the stochastic inflow input sets. These inflow volumes can be used with monthly mass balances typically used in essential supplies AWD planning as reviewed in Section 3.1 to indicate the likelihood of entering periods of water sharing plan suspension under different storage reserve assumptions. This approach is likely to give a better understanding of storage behaviour during the essential supplies phase of drought sequences, whereas the daily time step models will give a better understanding of the overall water supply impacts during normal operations from changes to the storage reserve.

### 3.3.1 Baseline climate series used for scenario modelling

The anticipated model scenarios will be built using data that are currently available (see review in Chapter 2), namely the instrumental historic series and the 10,000-year stochastic climate dataset. These two datasets will be used for baseline series modelling. Three model output series will be produced using these datasets:

- Series 1: Historic instrumental climate data up to the cutoff date specified in the water sharing plan
- Series 2: Historic instrumental climate data covering more recent drought sequences (up to 2020)
- Series 3: The paleo-stochastic 10,000-year sequence

### 3.3.2 Climate change series used for scenario modelling

For current and near future climate representation, two additional series will be created by modifying the 10,000-year paleo-stochastic climate series as follows:

- Series 4: a paleo-stochastic 10,000-year sequence with seasonal percentile scaling of evapotranspiration reflecting 2035 conditions. This sequence is designed to represent a plausible near future climate in the next 10 years, given that water sharing plans have a 10-year planning cycle. Changes to potential evapotranspiration are driven primarily by increased temperatures and are predicted to be significant enough to be represented in the near future modelling series. Projected changes in rainfall (including, in some cases, the direction of change) are less certain and are therefore not scaled in this model series. Evapotranspiration scaling will be undertaken using NARCliM 2.0 outputs.
- Series 5: a paleo-stochastic 10,000-year sequence scaled to 2050 using NARCliM 2.0 and the SSP3–7.0 emission scenarios. Given that the medium emissions scenario for NARCliM 2.0 will not be available until 2025, this project will use the GCM/RCM results with the SSP3–7.0 emissions scenario to estimate the greatest reduction in rainfall, allowing us to stress-test the modelled AWD process and associated supply reliability. The year 2050 was selected because it is soon enough to inform an adaptive pathway, yet not so far into the future that uncertainty increases and results diverge. The data in series 5 would

equate to a global temperature increase of 2.0 °C over pre-industrial levels by 2050.[3] The series 5 model runs are intended as a stress test.

The proposed model series are summarised in Table 2.

Table 2. Proposed model series

| Dataset no. | Description | Rationale |
|---|---|---|
| 1 | Observed data 1895–20XX | **Historic reference.** Existing water sharing plan specifications. |
| 2 | Observed data 1895–2020 | **Reference data updated to 2020.** Incorporates recent droughts in most plan areas. |
| 3 | 10,000-year paleo-stochastic data used in the quality assurance step | **A baseline data model series.** Best estimate of historic supply reliability risk for storage reserve size. |
| 4 | 10,000-year paleo-stochastic data factored with increased potential evapotranspiration @ 2035 | **A current climate model series.** Best estimate of risk from variability and change covering the current water sharing plan review period. |
| 5 | 10,000-year paleo-stochastic data factored with high emissions scenario rainfall and potential evapotranspiration changes @ 2050 under NARCliM 2.0 | **A stress test climate series.** An indication how far storage reserves may need to be pushed to maintain supply reliability. The driest scenario available with NARCliM 2.0. |

### 3.3.3 Model scenarios

The proposed model scenarios for each climate series are intended for the development of supply reliability response curves to changes in storage reserve volume.

Under each of the 5 climate input series, we propose to model at least 5 storage reserve settings, from which other potential storage reserve volumes can be inferred via interpolation:

- S0, the current storage reserve with the current minimum inflow sequence
- S1, the current reserve increased by 25% of the current minimum inflow sequence
- S2, the current reserve increased by 50% of the current minimum inflow sequence
- S3, the current reserve increased by 75% of the current minimum inflow sequence
- S4, the current reserve increased by 100% of the current minimum inflow sequence.

The key outputs from the model scenarios and the associated data analysis methods are presented in section 3.4. However, one of the key outputs from this scenario modelling method is the relationship between supply reliability and storage reserve. In designing this study to produce these outputs, we suggest that in future water sharing plans, supply reliability should

[3] For more information, see the NARCliM website: www.climatechange.environment.nsw.gov.au/projections-map.



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define storage reserve requirements, rather than historic storage reserves defining future supply reliability. If an expected supply reliability is prescribed, the storage reserve requirement can become adaptable to climate change.

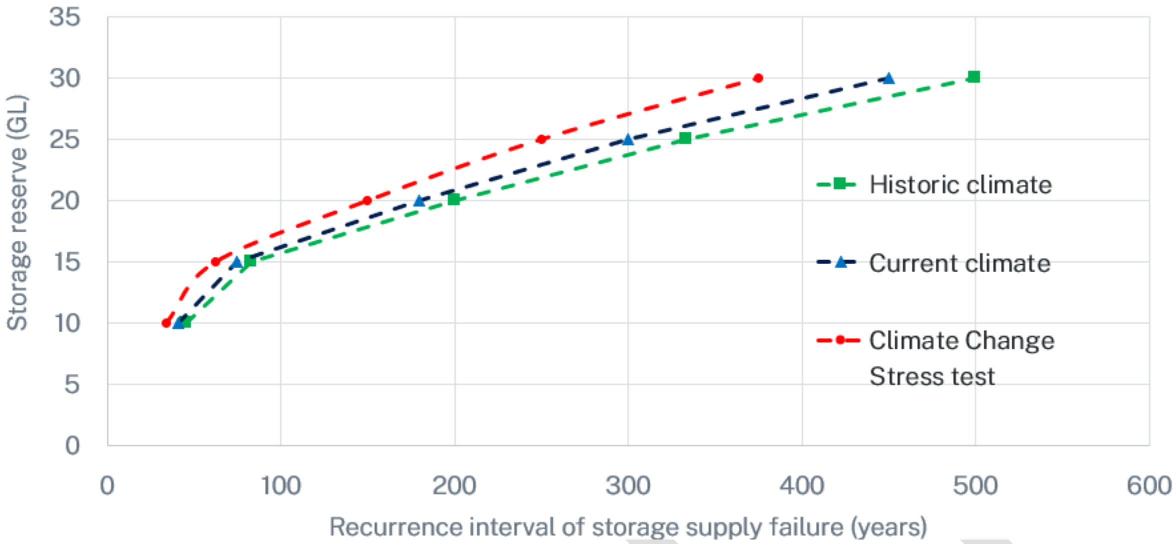


Figure 6. Example graph of average annual recurrence interval as a function of storage reserve

## 3.4 Data analysis

The analysis of model scenario results will systematically cover three main areas of model data interrogation:

- hydrologic metrics
- environmental metrics
- economic metrics.

This section only covers hydrologic metrics. Separate methodology documents will be produced to describe the environmental and economic analysis. The outcomes of the environmental and economic analyses are likely to be important in arriving at an appropriate storage reserve.

Table 3 outlines the standard hydrological metrics expected to be generated for each valley. Any additional valley-specific metrics identified will be outlined in forthcoming reports on the outcomes of the review in each valley. The analysis metrics include allocations to each licence category, diversions, storage behaviour and flow.

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Table 3. Summary of hydrologic metrics

| Category | Component | Rationale |
|---|---|---|
| **Mean annual diversions** | • General security<br>• High security<br>• Domestic and stock*<br>• Local water utilities<br>• Supplementary<br>• Planned environmental water (PEW)<br>• Inter-valley transfer (where relevant) | Determine the impact of model scenarios on diversions |
| **Average Allocations** | • General security average allocations and account balances on 1 July, 30 September and 30 June and average over whole period<br>• High security average allocation on 1 July, 30 September and 30 June<br>• Conveyance average allocations and account balances on 1 July, 30 Sept and 30 June and average over whole period<br>• Local water utility, major utility and domestic stock average allocations on 1 July, 31 December and 30 June<br>• Account-based average PEW effective allocations on 1 July, 30 September and 30 June<br>• Occurrence of no allocations for each licence type | • Understand the impact of model scenario on allocations, and carryover where applicable, for different water users.<br>• The Basin Plan requires protection of the effectiveness of PEW.<br>• Improve understanding of how often allocations are zero |

| | | |
|---|---|---|
| **Storage behaviour** | • Frequency and volume of spills<br>• Average yearly volume of spills<br>• Percentage of time below nominated thresholds | • Climate change is predicted to bring more extremes, which may mean more extreme floods, and holding a higher storage reserve may result in more spills and loss of productivity. These metrics assist us in understanding the impact that the volume held in the storage reserve will have on spills.<br>• This metric shows how often a dam will fall below certain thresholds in future climate scenarios, providing more understanding of when the Extreme Events Policy may be triggered or when security may be reduced for high priority licences. |
| **Mean annual streamflow** | At targeted gauges | Determine changes to hydrology and flow patterns, particularly cease to flow periods for towns and key basic landholder rights reaches. The environmental and economic impact assessments will determine impacts based on modelled changes to streamflow data. |
| **Transparent and translucent flows** | • Average volume released<br>• Percentage of time flows are activated | Understand how future climate scenarios may trigger transparent and translucent flows and the subsequent environmental impacts of these flows. |
| **End-of-system flow releases** | Number of days the minimum flow rule was met | Understand the impact of storage reserve volumes on meeting end-of-system flow targets |
| **Replenishment flow releases** | • Percentage of years fully delivered<br>• Average volume released | Understand the impact of holding different storage reserve volumes on replenishment flow delivery. There is significant operator discretion in how replenishment flows are delivered, and they can be met by tributary inflows, so they may be triggered differently in models compared to how they are used in river systems. |
| **Level of security** | Level of security for high priority needs | Understand how the supply reliability changes for high priority users under different storage reserve and climate scenarios |
| **Supplementary events** | Number and duration of supplementary events | To understand the impact of model scenarios on supplementary events |

* The stock and domestic rights usage in the river system is included in the water sharing plans. However, as we do not have usage data, and the relevant volumes are comparatively small compared with other water balance components, this usage is generally treated as an unaccounted difference in the operational and planning models. We are providing an indicator based on flow along a river they can access.

## 3.5 Reporting framework

The proposed reporting framework for the review method has two components:

1. a methods report, which will document the model input data, models and data processing methods and provide an overview of the entire project and details of the modelling methodologies in valley-specific reports
2. a series of valley-specific reports containing the results of the AWD review, the quality assurance analysis and the results of the storage reserve scenario modelling.

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# Appendix 1

Provision within the Water Sharing Plan for the NSW Border Rivers Regulated River Water Source 2021 requiring review of the 'Maintenance of water supply' clause.

*57 Maintenance of water supply*

*(1) In this clause, the period of lowest accumulated inflows to the water source is identified by flow information held by the Department prior to 1 July 2009.*

*(2) The operator must operate the water supply system in such a way that water would be able to be supplied during a repeat of the period of lowest accumulated inflows to the water source, to meet the following:*

*(a) the annual water requirements of persons exercising domestic and stock rights and native title rights,*

*(b) available water determinations of 100% of share components for domestic and stock access licences and local water utility access licences,*

*(c) available water determinations of 1 ML per unit share for regulated river (high security) access licences.*

*(3) For the purpose of subclause (2), the operator must set aside sufficient volumes of water from inflows into the water source and in reserves held in Pindari Dam and Glenlyon Dam water storages.*

**Note.** Reserves is defined in the Dictionary.

*(4) During the first 5 years of this plan, the Minister will undertake a review of this clause that considers the following:*

*(a) options for redefining the period of lowest accumulated inflows to the water source,*

*(b) whether different periods should apply to different categories of access licences,*

*(c) the impact of any options for change on planned environmental water and each category of access licence, and*

*(d) the views of stakeholders and the broader community.*

*(5) On the basis of the review referred to in subclause (4), the Minister may make such amendments to this clause as are reasonably necessary to not jeopardise the critical needs of basic landholder rights, domestic and stock access licence holders and local water utility access licence holders.*

*(6) Any amendments made under subclause (5) cannot substantially alter the long-term average annual amount of water able to be extracted under water access licences.*

**Notes.**

1 If satisfied that it is in the public interest to do so, the Minister may amend this clause under s.45 (1) (a) of the Act to such an extent that it substantially alters the long-term average annual





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amount of water able to be extracted under water access licences. If this Page 46 Water Sharing Plan for the NSW Border Rivers Regulated River Water Source 2021 occurs, compensation may be payable under chapter 3 Part 2 Division 9 of the Act.

2 Section 10.28 of the Basin Plan requires that a water resource plan must ensure there is no net reduction in the protection of planned environmental water from the protection provided under State water management law immediately before the commencement of the Basin Plan

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# Appendix 3: Validating climate risk data for use in Border Rivers water sharing

# Validating climate risk data for use in Border Rivers water sharing

Allocation decisions are currently made based on climate data from 1890-2009. Alternative data needs to be assessed as a requirement of the water sharing plan. Climate risk data developed for the Regional Water Strategies is a potential source of alternate data. However, this data needs to be validated before being used in water sharing. Validation shows the how suitable the data is for water sharing planning purpose

## Introduction

To allocate water in the NSW Border Rivers Regulated River Water Source (Border Rivers) sustainably, we must understand climate related risks to water security. In the Border Rivers, these risks have been estimated using instrumental measurements of rainfall, streamflow, and evaporation from 1890-2009. We use these measurements to estimate how much water should be stored in Glenlyon and Pindari Dams to meet future high priority needs.

As per the Border Rivers Water Sharing Plan (WSP) Clause 57(4), alternate sources of climate data must be considered. One source is the paleo-stochastic data developed for the Regional Water Strategies (RWS).

This data was extensively validated against instrumental climate and headwater catchment flow distributional statistics. This validation process showed that the paleo-stochastic data was suitable for modelling the RWS. However, before we can use the data for a different purpose, further validation is needed to determine how suitable it is for use to inform water sharing arrangements. The suitability of the data will vary depending on what aspect of the water sharing arrangements are being investigated, and whether any decision that needs to be made relies on an absolute value, or a change relative to a baseline, and how much of a change that might be.

In this report, we validate the RWS paleo-stochastic data against water management outcomes in the Border Rivers. Paleo-stochastic outputs from the Border Rivers Source model (Border Rivers model) are compared against instrumental model outputs and observations. Metrics related to water management (e.g., water allocations per licence type, town water supply shortfalls, ecological condition) are evaluated.

## Climate risk data developed for the RWS.

The RWS paleo-stochastic data was produced for ~3000 climate variables at stations across NSW (including 113 variables for the Border Rivers). The paleo-stochastic data was produced from a stochastic model calibrated to instrumental measurements (e.g., rainfall stations) and paleoclimate data. 10,000 years of synthetic daily climate data was generated for each station. This data better characterises long-term climate risks to water security from natural variability.

Stochastic models are statistical risk models often used in water management. They are calibrated using instrumental climate data, and NSW has also introduced a multi-decadal variability pattern by using an Interdecadal Pacific Oscillation signal derived from paleological data. They are then used to generate synthetic climate timeseries with similar statistics to the instrumental records, but with a different sequencing of wet/dry years.

Each point in the synthetic timeseries is comprised of a randomly generated number, which mimics the inherent randomness of climate timeseries. Compared with instrumental measurements, the random sequencing of stochastic timeseries can produce more extreme – but still plausible – events such as droughts. We can then consider these droughts in our planning.

For the RWS, paleoclimate data was also used in stochastic model calibration. Paleoclimate data refers to climate data derived from naturally forming 'layers', such as tree-rings and ice-cores. The properties of these 'layers' indicate what the climate was like at the time of formation. For example, a wide tree-ring can indicate a wet year, a narrow tree-ring a dry year. These 'layers' – also referred to as paleoclimate proxy data – form over hundreds to thousands of years.

Using paleoclimate data gives us a better sample of natural climate variability (i.e., the length of wet/dry periods) than using only the short instrumental measurements. The RWS data method used proxy measurements to estimate the length of wet and dry periods, then created wet/dry synthetic data using stochastic models (hence the term 'paleo-stochastic' data).

Paleo-stochastic data better characterises climate variability and, by extension, climate risks to water security. However, this is modelled data. It must be validated against observations.

For the RWS, paleo-stochastic data was validated against observed rainfall, evaporation, and streamflow data. The data was deemed satisfactory for RWS purposes (i.e., assessing long-term water security options). However, use in water sharing requires additional validation against shorter -term water management outcomes (e.g., ensuring that allocations under paleo-stochastic climate are realistic).

Validation with respect to water management outcomes requires running the Border Rivers Source model with paleo-stochastic input data. Outputs can then be compared against either:

a) observations or,

b) outputs from the same model run using instrumental inputs if observations are insufficient.

The selection of appropriate metrics that capture key water management outcomes is a crucial part of this process.

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# Selection of evaluation metrics

When evaluating stochastic model outputs, the chosen metrics should be related to the modelling goal. For example, metrics that describe management outcomes (e.g., water allocations for different license types) and management-relevant statistics (e.g., storage behaviour) are favoured over those that describe general climate conditions (e.g., the mean and standard deviation of annual flow). Table 1 lists key metrics that we chose to evaluate the Border Rivers model run using paleo-stochastic input data.

Table 1: Proposed metrics for evaluating the use of stochastic data in the Border Rivers model.

| Proposed Metric | Justification | Data Available |
|---|---|---|
| 18 and 24-month minimum storage inflow percentile – Pindari and Glenlyon combined | Used in water allocations. | Instrumental Source run and observed inflow (derived from back-calculation). |
| 18 and 24-month storage inflow exceedance curve – Pindari and Glenlyon combined | Used in water allocations. | Instrumental Source run and observed inflow (derived from back-calculation). |
| End of Stream flow – daily and annual exceedance curves | End of stream represents integration of all upstream modelling choices and input data | Instrumental Source run. No observations available for EOS node in Source. However, three gauges immediately upstream (416001, 416028, and Little Weir) are available. |
| End of Stream flow – monthly median percentile | End of stream represents integration of all upstream modelling choices/input data | Instrumental Source run. No observations available for EOS node in Source. However, two gauges immediately upstream (416001 and 416028) are available. |

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| Proposed Metric | Justification | Data Available |
|---|---|---|
| **Storage volume – daily and average annual exceedance curve** | Used as a proxy for implementation of Extreme Events policy and for calculating supply shortfalls. Combined storage is necessary as model does not simulate harmony rules consistent with operational characteristics. | Instrumental Source run and observed storage volume. |
| **Storage volume – time below 50%, 25%, 10%, and 5% thresholds (daily timeseries)** | Used as a proxy for implementation of Extreme Events policy and for calculating supply shortfalls. Combined storage is necessary as model does not simulate harmony rules consistent with operational characteristics. | Instrumental Source run and observed storage volume. |

# Evaluation approach

The stochastic data evaluation approach used for water sharing plan is different to the methods used by DPE Water when evaluating rainfall-runoff or river system model outputs. This is because:

1. stochastic timeseries generate different sequences of wet and dry years compared to the observed sequence; and
2. stochastic timeseries are much longer than the corresponding observation time series.

Stochastic timeseries are designed to have similar statistics to the observed timeseries, but with different sequences of wet and dry years. This means that conventional evaluation metrics which compare sequential ‘pairs’ of observed and modelled data (e.g., Pearson correlation and Nash-Sutcliffe Efficiency), are not suitable for stochastic data evaluation. Instead, we compare the similarity between management-relevant statistics of the data.

However, these statistics cannot be directly compared. For example, the 10,000-year minimum stochastic flow and the 130-year minimum observed flow will not be similar because the longer timeseries is more likely to contain more extreme low flow events.

This is a feature of stochastic datasets – they are designed to contain more variability than the instrumental data. More extreme wet and dry periods can be generated because stochastic datasets are longer and contain randomness.

Therefore, differences in the timeseries length and variability must be accounted for when evaluating stochastic statistics. We do this by deriving a 'stochastic distribution'.

## Deriving stochastic distributions

A stochastic distribution (sometimes referred to as a 'sampling distribution') is used to evaluate stochastic timeseries. For a statistic or metric of interest, a stochastic distribution can be derived using these steps:

1. Identify the length of the corresponding observed timeseries (e.g., 130 years).
2. Separate the stochastic timeseries into non-overlapping blocks. Each block is the same length as the observed timeseries (e.g., 130 years). These blocks are often referred to as 'stochastic replicates.
3. For each replicate, calculate the statistic or metric of interest (e.g., mean, standard deviation). These statistics are the 'stochastic distribution'.

The stochastic distribution is calculated using timeseries of equal length to the corresponding instrumental data. Because differences in length have been accounted for, we can then compare and evaluate the stochastic distribution against observed statistics.

The metric calculated for each stochastic replicate may be very different from the instrumental metric, because of the inherent randomness. However, we expect the stochastic distribution to consistently contain the instrumental statistic and, ideally, the stochastic median to be close to the instrumental statistic, although that will not always be the case depending on which statistical characteristics of the instrumental data the stochastic data was calibrated to. This is why we look at the entire stochastic distribution to see if the instrumental values lie somewhere within.

Nevertheless, stochastic data is modelled data, and all models contain uncertainties. It is possible for the stochastic data to be biased or a poor fit to the instrumental data. Where possible, the distributions of metrics should be evaluated as well as key summary statistics (e.g., the mean). This allows us to assess whether high/low values are also adequately captured.

## Evaluating stochastic distributions

There are numerous approaches for comparing observations and stochastic distributions. The approach most used by DPE Water is a visual comparison between the datasets. However, this approach requires considerable expert judgement to determine whether the datasets are sufficiently similar.

Other methods systematically categorise the performance as 'good', 'fair', 'poor' or similar using pre-determined quantitative criteria. These methods provide clear communication of the results to nonexperts but have been criticised for being subjective (i.e., the criteria selected by the analyst may not be relevant or important for a project or an outcome).

In evaluating the stochastic distributions for this project, we have combined these broad methods by providing:

a) A visual comparison of the distribution of data for each metric, and

b) A suite of performance indicators that provide a quantitative assessment of the fit between the stochastic metric and the observed metric.

The visual evaluation and performance indicators are different depending on whether the comparison is between a single instrumental statistic and a stochastic distribution or two distributions.

## Evaluating stochastic distributions using a single statistic

An example of a single statistic comparison is median monthly end-of-stream flow. We evaluated instrumental statistics by calculating the (a) percentile rank within the stochastic distribution of the instrumental statistic and (b) absolute bias of the instrumental statistic with respect to the stochastic median. We considered a percentile rank within the $5^{th}$ – $95^{th}$ percentile range as indicative of good stochastic model performance.

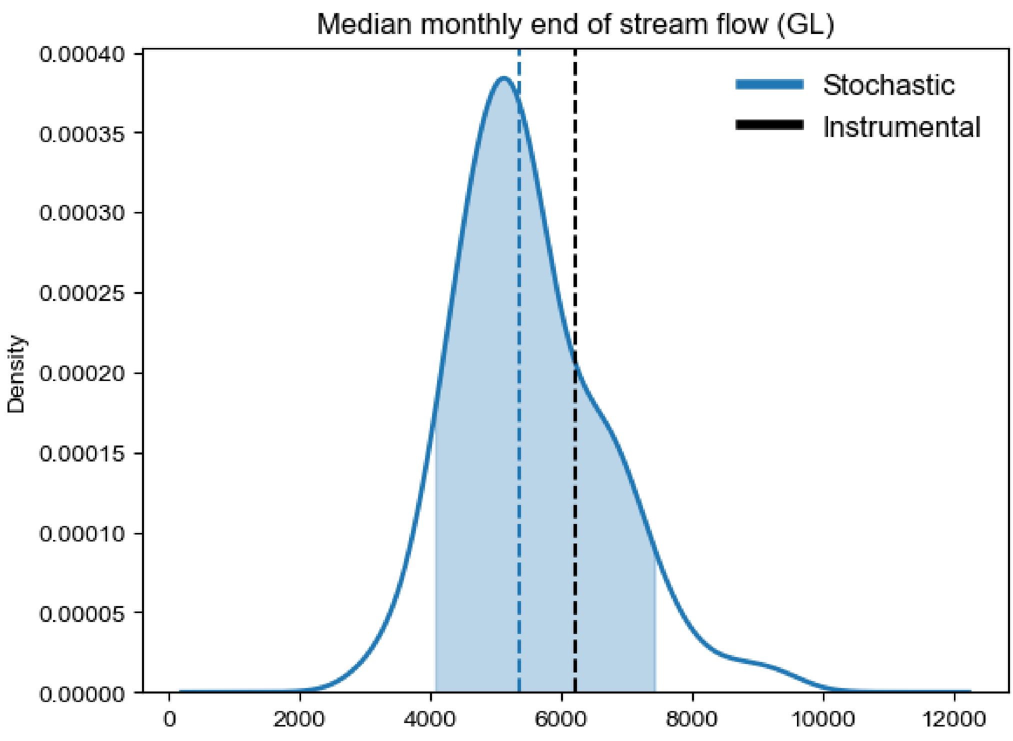


Figure 1. Comparison between a stochastic distribution (blue) and instrumental metric (black). The shaded interval is the 90% confidence interval of the stochastic distribution.

## Evaluating stochastic exceedance probabilities against instrumental

For other statistics, such as the daily and annual exceedance curves for end-of-stream flow, we calculated exceedance probabilities directly from both the instrumental and stochastic data. For exceedance curves, the instrumental data has 100 derived values (data percentiles 1 to 100), and the stochastic distribution is a matrix of size n x 100 percentiles where n is the number of stochastic replicates. A visual representation of this data is provided in Figure 3.

We calculated the same performance measures as in the previous example although their definitions are slightly different.

- The bias is calculated by comparing the instrumental exceedance probabilities to the stochastic median exceedance probability, that is, the sum across all 100 values.
- Capture is the percentage of instrumental exceedance probabilities that fall within the 5$^{th}$ and 95$^{th}$ percentiles of the stochastic distribution.
- The skill score is calculated by comparing the instrumental distribution to the stochastic distribution (see Perkins Skill Score section).

Additionally, we calculate the statistical significance of the difference between the exceedance curves by running a two-sample K-S test (comparing the instrumental exceedance curve with the stochastic median exceedance curve). The K-S statistic describes similar information to the skill score and the capture percentage, but also provides a p-value which can be helpful to determine if a low skill score or capture percentage correspond to a statistically significant difference between the distributions. For the K-S test, the null hypothesis is that there is no difference between the distributions. A p-value > 0.05 confirms the null hypothesis, that the difference between the distributions is not significant.

## Perkins Skill Score

The Perkins skill score (skill score) provides a further measure of the fit between the instrumental and stochastic data. The skill score is a simple measure of the similarity between two distributions. This metric calculates the cumulative minimum value of two distributions of each binned value, thereby measuring the common area between the distributions. If the distributions overlap perfectly, the skill score will equal 1. If the stochastic data poorly captures the observations, the skill score will be close to 0.

The benefit of the skill score is it provides a quantitative measure of similarity comparable to what would be assessed by eye. Figure 2 shows example instrumental and stochastic distributions used to calculate the skill score. Again, they are very similar as the data in most bins overlaps.

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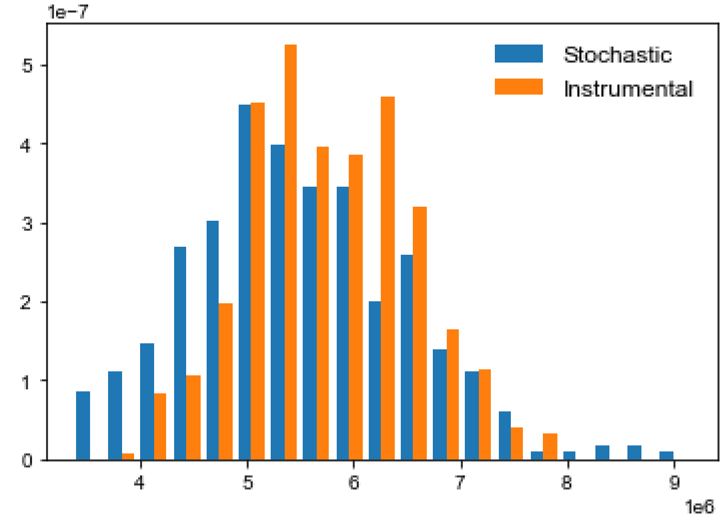


Figure 2. Example of the calculation of the Perkins skill score. The metric represents the degree of overlap between two binned distributions (blue and orange). Here, 20 bins are used to represent the data.

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# Evaluation results

The bias and skill score results for the metrics referenced in Table 1 are summarised in Table 2 for inflows and outflows, Table 3 for storage levels, Table 4 for allocations, and Table 5 for diversions.

## Flow evaluation

Table 2. Inflow and outflow performance metric results

| Statistic | Skill Score | Absolute Bias (%) | % Capture | P-value | Percentile Rank |
|---|---|---|---|---|---|
| 18-month inflow | 0.91 | 6.5 | 90 | 0.91 | n/a |
| 24-month inflow | 0.90 | 7.1 | 92 | 0.92 | n/a |
| 18-month minimum inflow | n/a | 27.3 | n/a | n/a | 74.3 |
| 24-month minimum inflow | n/a | 12.6 | n/a | n/a | 33.8 |
| end-of-system daily flow | 0.99 | 6.7 | 100 | 1.00 | n/a |
| end-of-system monthly median flow | 0.76 | 5.8 | n/a | n/a | 75.7 |
| end-of-system annual flow | 0.92 | 9.7 | 97 | 0.97 | n/a |

The performance metrics for 18-month inflows 24-month inflows and end-of-system flows show a high level of agreement between the observations and stochastic data greater than 0.9 in most cases with biases between medians less than 10%. The result for inflows (displayed graphically at Figure 3) is consistent with the results of our climate data quality assurance processes.

The bias result for 18-month and 24-month minimum inflows were also assessed. Context for the result of this is shown in Figure 4, which shows in greater detail the higher-exceedance lower-flow portion of the full range exceedance plot from Figure 3. This shows that the lower flows, while mostly within the 5$^{th}$ to 95$^{th}$ confidence limits of the stochastic distribution, are consistently higher than the median of the stochastic distribution. This is related to the simulation of the multi-annual distribution of stochastic rainfall, which is dry biased at the low end of the distribution for many, but not all rain gauges.

The quality assurance method for minimum-inflows is then targeted at the most extreme value from the observed values, i.e., the 100$^{th}$ percentile exceedance value. The stochastic distribution of this

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statistic is shown at Figure 5, with the median value of the stochastic distribution and the observed minimum inflows shown for comparison. The bias result in Table 2 of 27.3 % and 12.6 % respectively is the percent difference between these values. The result also shows that the observed minimum inflows fall well within the 5th – 95th percentile confidence limits. For the 18-month minimum inflow, the observed value is exceeded by about 25% of the stochastic minimum inflows, and the 24-month observed minimum inflow is exceeded by 67% of the stochastic minimum inflows.

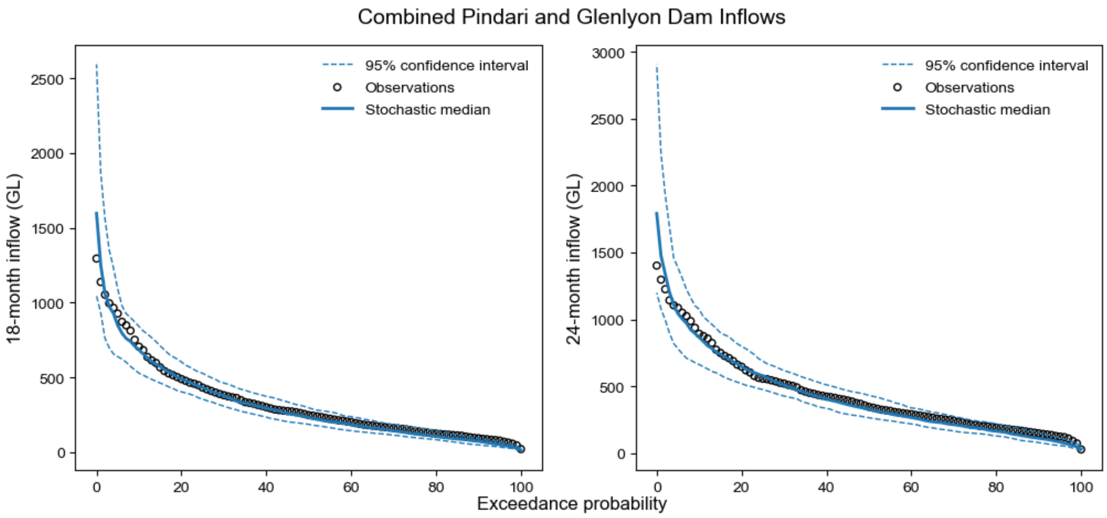


Figure 3. Quality assurance exceedance plots for 18- and 24-month combined inflows to Pindari and Glenlyon dams.

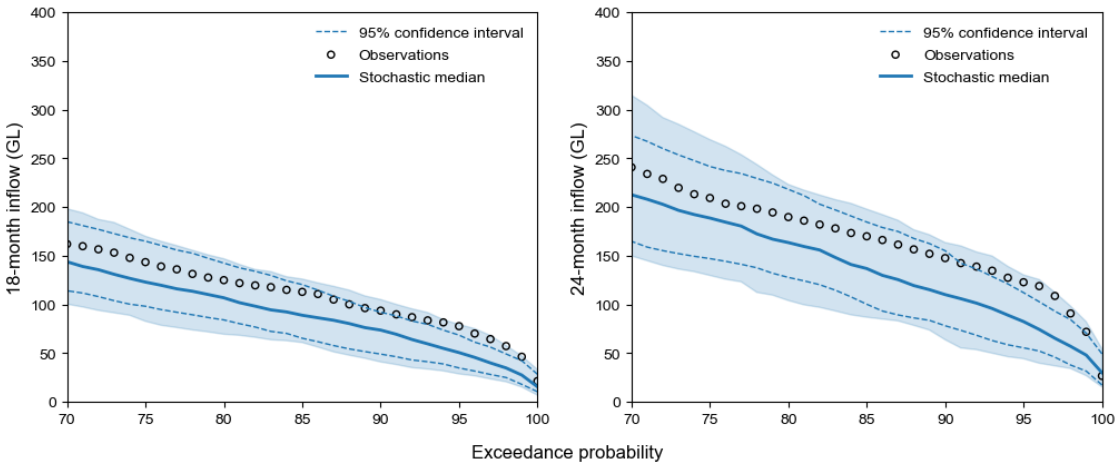

Figure 4. Partial quality assurance exceedance plots for 18- & 24-month combined inflows to Pindari and Glenlyon dams.

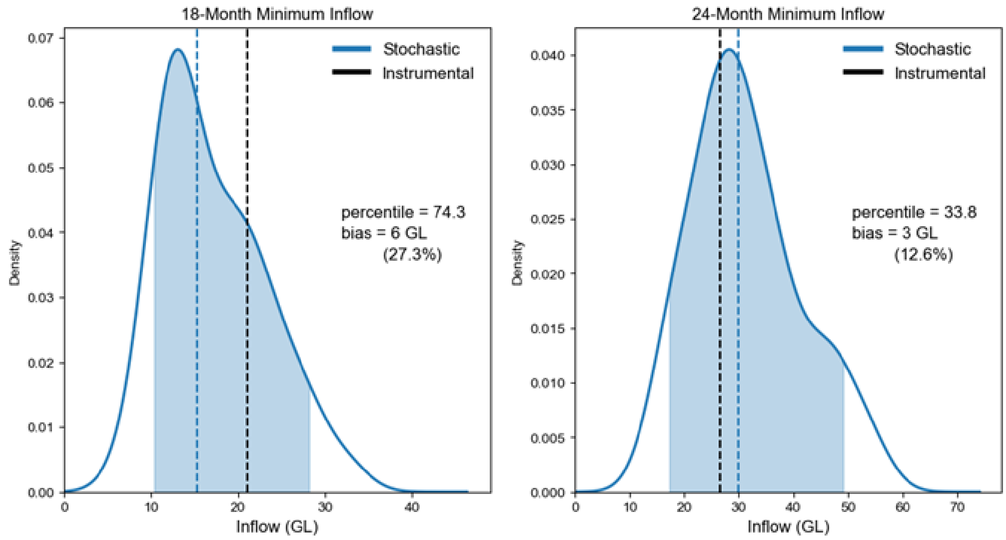


Figure 5. Quality assurance distribution plots for 18- and 24-month combined minimum inflows to Pindari and Glenlyon dams.

The results for end-of-system flows are after a series of water management and physical process related water balance calculations in the river system model and suggest that overall system water balance results from using stochastic data are consistent with results using observed data. Plots of these distribution are provided in Figure 6, showing the closeness of the fit of the observed values with median value of the stochastic distribution, and almost fully within the confidence limits. The observed and stochastic distributions of the observed median monthly inflows is shown in Figure 7.

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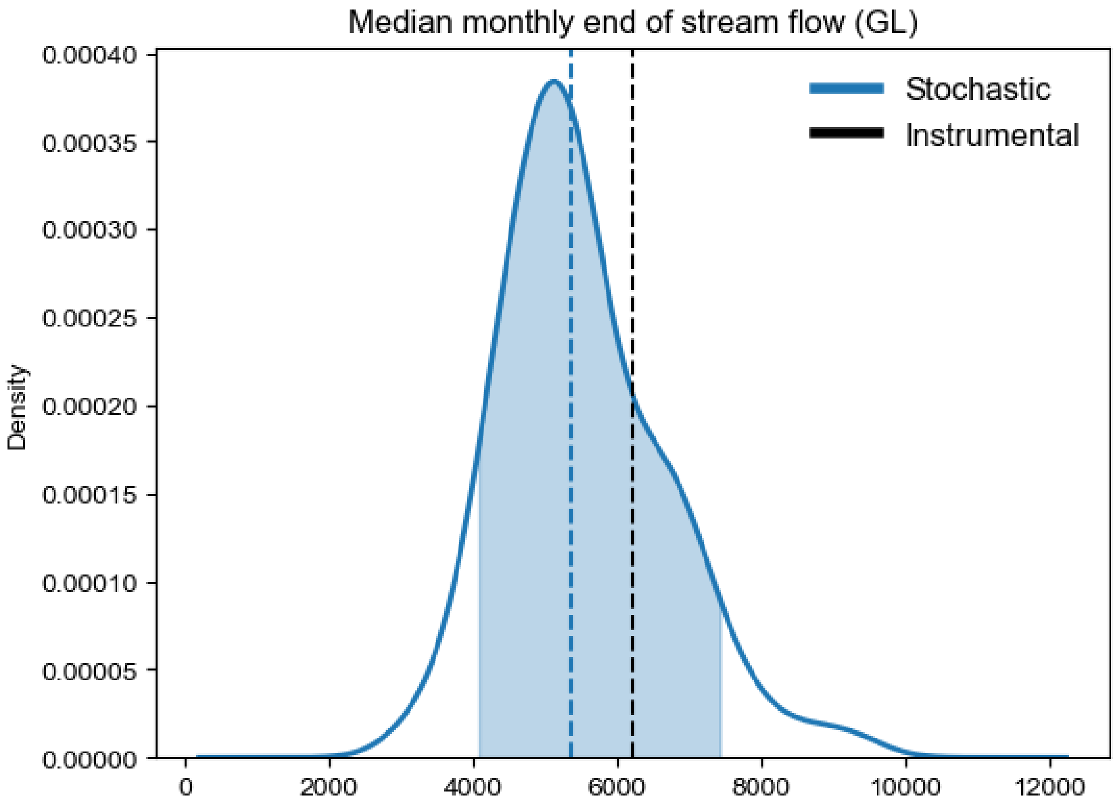


Figure 6. Observed v stochastic quality assurance exceedance plots for daily and annual combined end-of-system flows.

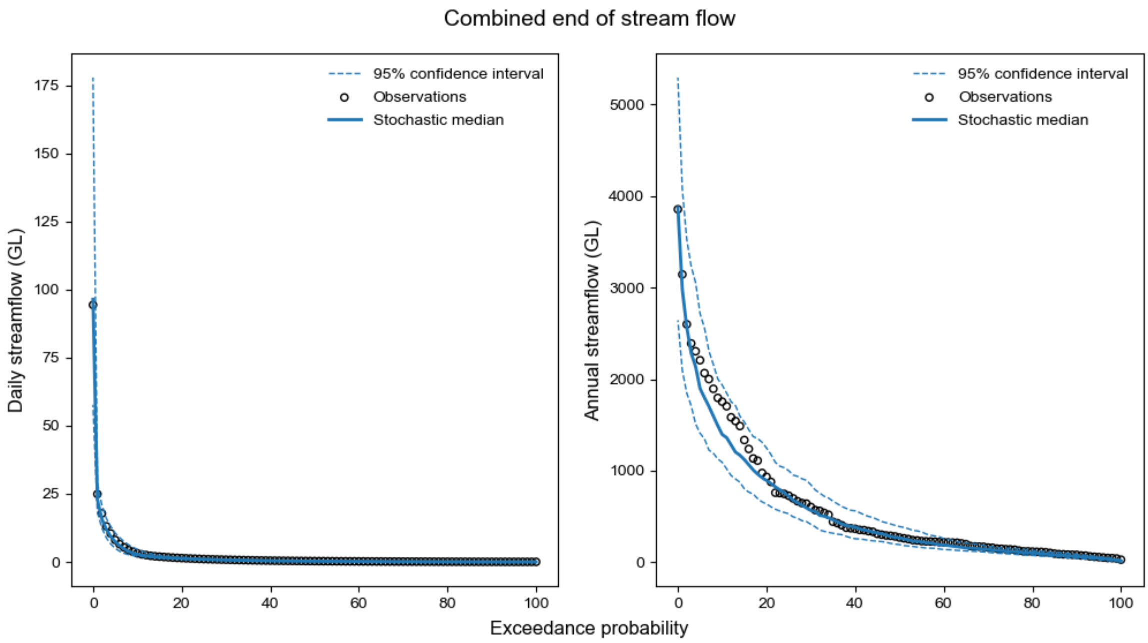


Figure 7. Observed v stochastic quality assurance frequency distribution plot for median monthly end of system flows.

## Storage level evaluations

Table 3. Storage level performance metric results

| Statistic | Skill Score | Absolute Bias (%) | % Capture | P-value |
|---|---|---|---|---|
| **Daily combined storage** | 0.90 | 3.9 | 100 | 0.97 |
| **Average annual combined storage** | 0.85 | 4.1 | 98 | 0.71 |

The results for overall storage have skills scores greater than 0.8 and absolute biases less than 5%, indicating the volumes in storage determining allocation related major water balance components have results consistent with those using observed data. The exceedance plots for these statistics are shown at Figure 8. The observational statistic tracks the median of the stochastic statistic closely for values greater than the 50$^{th}$ exceedance probability, with a progressively increasing positive bias for higher exceedance values (lower storage levels). This is consistent with the results from the inflows assessment where the stochastic values have a dry bias. This does not necessarily mean the stochastic data is performing poorly. It means we should investigate these metrics in more detail to understand why the stochastic and instrumental distributions are less similar than we might expect.

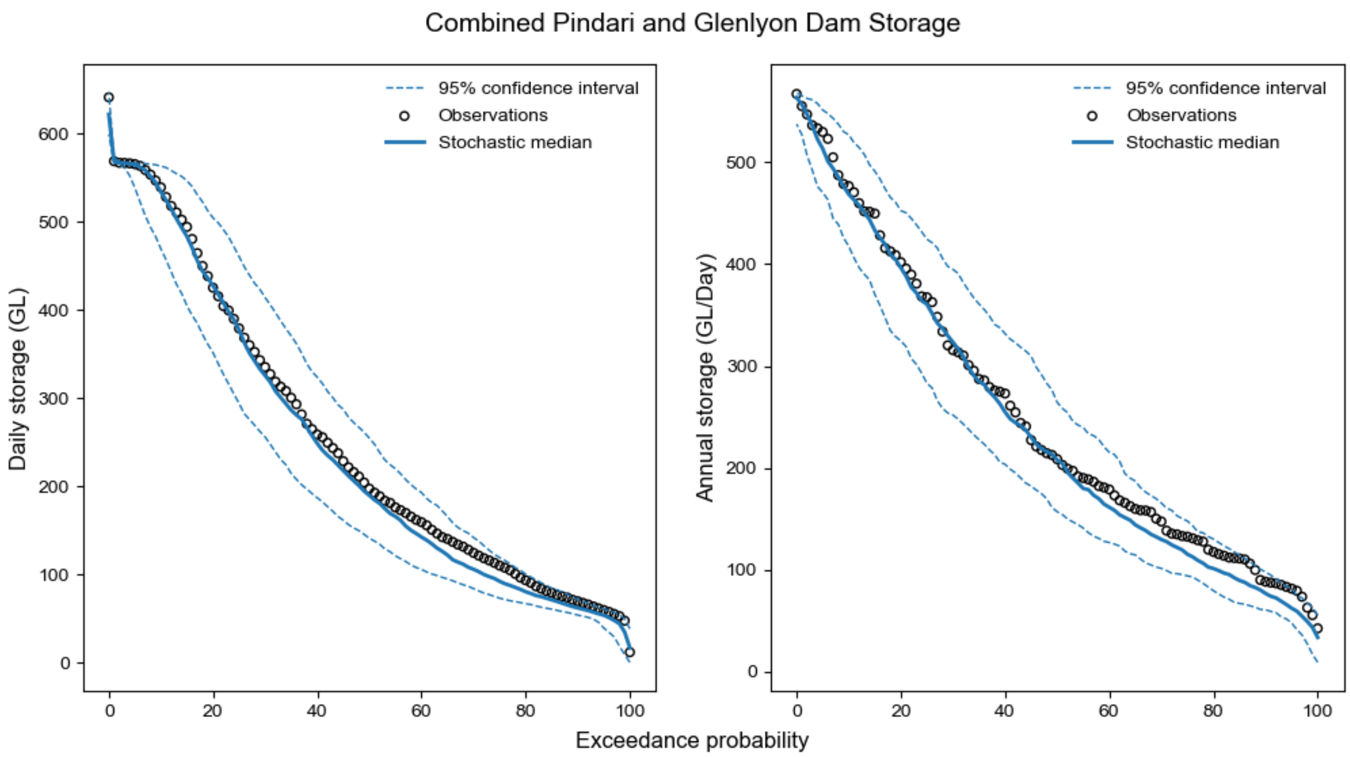


Figure 8. Quality assurance exceedance plots for combined storage in Pindari Dam and Glenlyon Dam at daily time step and for average annual values

This dry bias in the inflow data also manifests in the statistics for the time spent below storage thresholds, with performance metrics in Table 4 and distributions of these statistics shown in Figure 9. The stochastic distribution is also dry biased for low storage thresholds (time below 10%) due to the lower low flows. Time below 10% storage has a high percentile rank and a very large relative bias. However, the instrumental metric is within the $5^{th}$-$95^{th}$ confidence interval of the stochastic distribution and the absolute bias (14 days per 130 years) is small. The bias for time storage levels below 5% are much higher because the absolute bias (3 days per 130 years) is negligible.

Table 4. Storage level performance metric results

| Statistic | Percentile Rank | Absolute Bias (%) |
|---|---|---|
| **% Storage below 50%** | 43.2 | 2 |
| **% Storage below 25%** | 11.5 | 29.7 |
| **% Storage below 10%** | 10.8 | 87.7 |
| **% Storage below 5%** | 37.8 | 175 |

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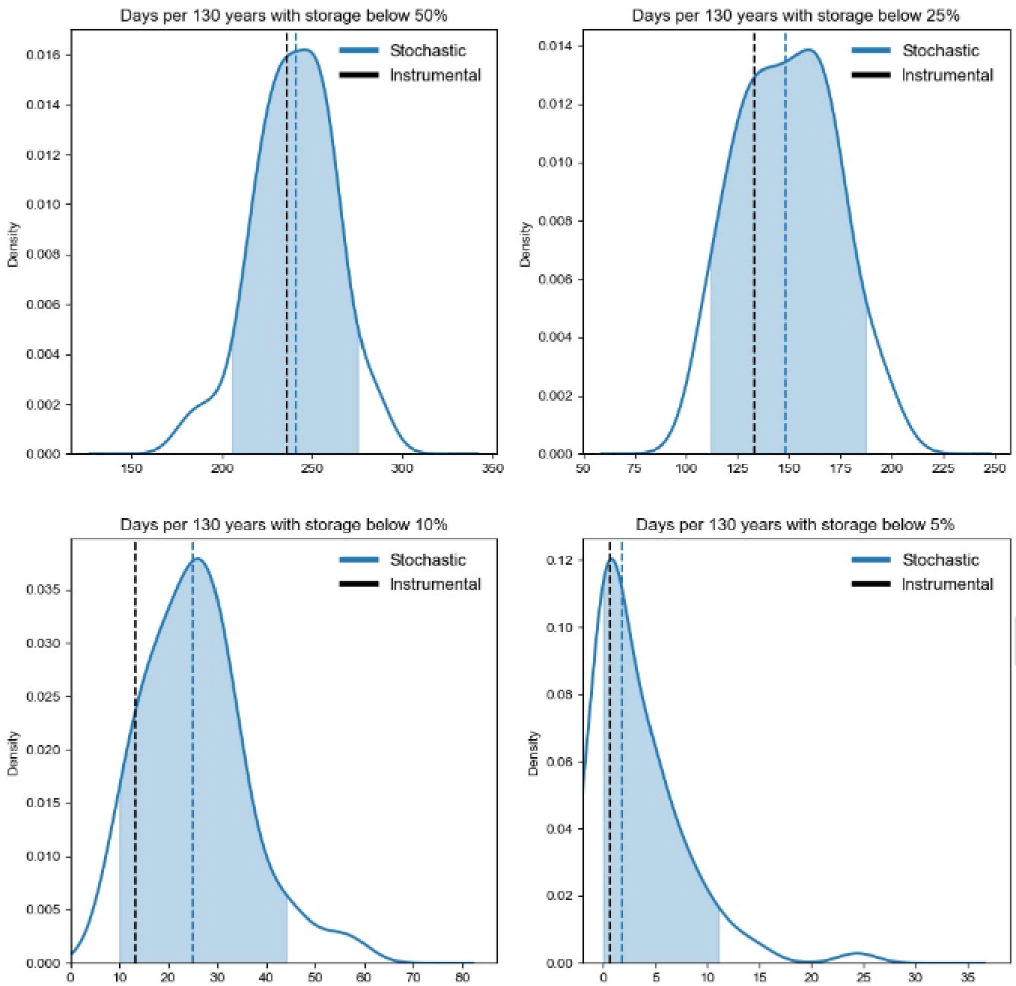


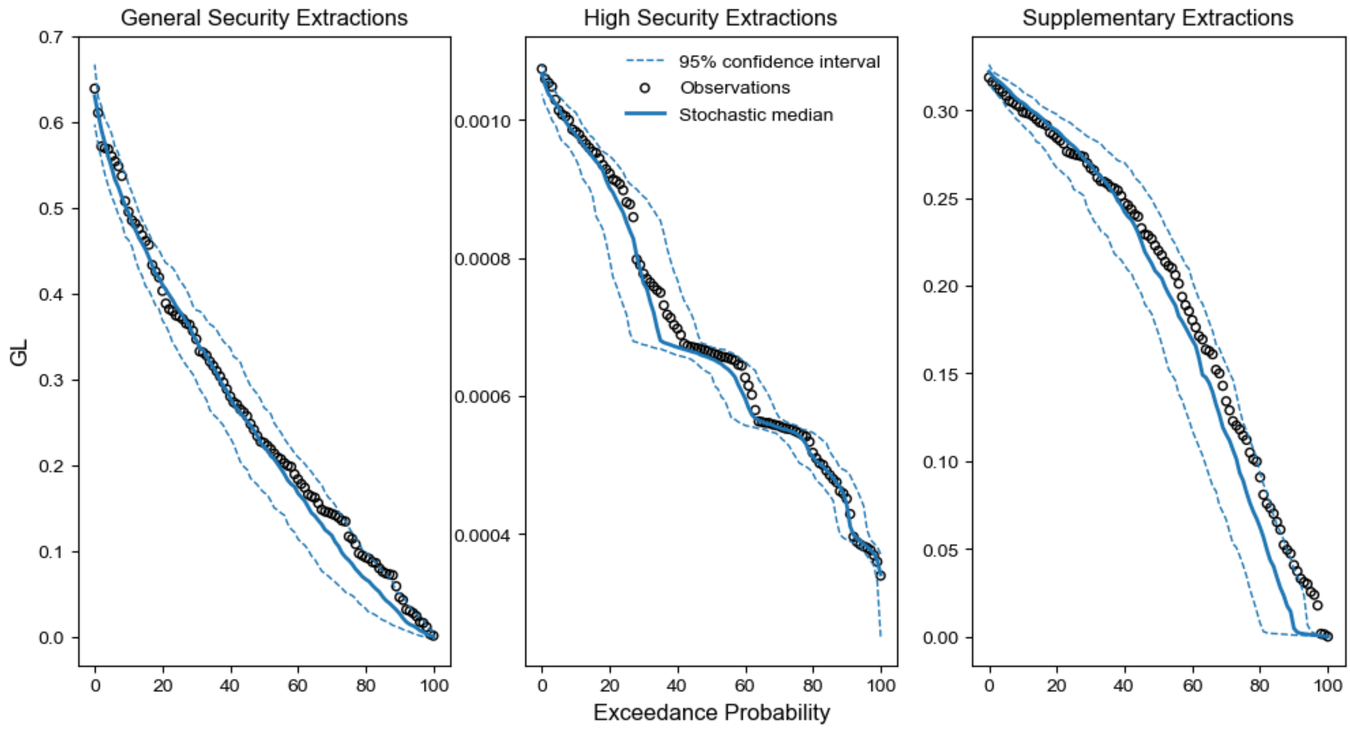

Figure 9. Observed v stochastic quality assurance frequency distribution plot for number of days combined storage levels below thresholds over 130-year period.

## Extractions

Table 5. Storage level performance metric results

| Statistic | Skill Score | Absolute Bias (%) | % capture | P-val |
|---|---|---|---|---|
| GS annual extractions | 0.85 | 5.2 | 95 | 0.71 |
| HS annual extractions | 0.88 | 1.9 | 100 | 0.97 |
| Supplementary annual extractions | 0.84 | 6.8 | 85 | 0.71 |

The skill scores for annual extractions for all licence types are greater than 0.8 and absolute biases less than 7%, with high capture values and high P-values, indicating that using stochastic climate data results in distributions of diversions for all licenced categories consistent with those using observed data. This is borne out by the graphical representation of the exceedance distributions of observed and stochastic in Figure 11. For the greater part of the distribution the results for the observational distribution track the median of the stochastic distribution for the higher to median values, with divergence in the lower diversion – higher exceedance probability part of the



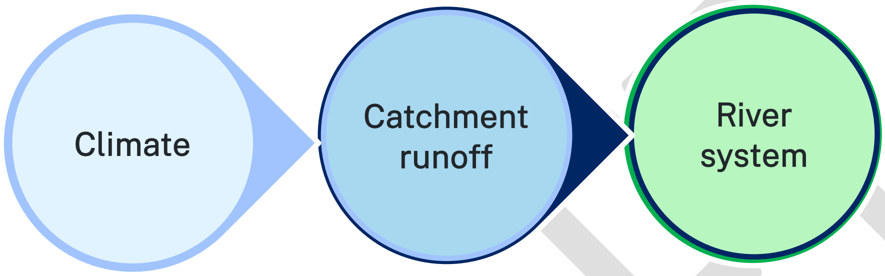

distributions. This is possibly linked to the dry bias discussed in the section on inflows.

Figure 10. Observed v stochastic quality assurance exceedance plots for high security, general security and supplementary access annual extractions.

# Discussion

## General

This paleo-stochastic climate risk data for the NSW Border Rivers regional water strategy has now been quality assured in three different sequential stages (Figure 16). Climate is the key natural driver of spatial and temporal water availability, which in turn results in variability outcomes for




different water dependent sectors

Figure 11. Stages of climate and water modelling quality assurance

1. The first stage examined the ability of the generated stochastic rainfall and potential evapotranspiration to reproduce key statistics in recorded data. This step was completed prior to it being used in the water models. The series of tests developed by the researchers, as well as an independent assessment by the department.
2. This was followed by an assessment of the catchment runoff produced using that quality assured climate data. We found in our early stage of using this stochastically generated climate data that even though it passed the initial quality control process, the runoff generated using that data in our calibrated rainfall runoff models had significantly different statistical characteristics compared to runoff generated using instrumental data.

   This testing was done systematically with all our calibrated runoff models. In the cases where we found the discrepancies were too high, and likely to cause biases in our river system models, then we would work with the researchers to revise the stochastic data that was an input to that runoff model with a different parameterisation or bias correction to produce modelled runoff with acceptable statistical characteristics.
3. The 3rd stage of this QC process is presented in this report, where both the climate data directly and the flow data from the runoff models was input to the river system models. The

quality control in the first two stages reduces the likelihood of large biases in the outputs of the river system model. Nevertheless, this needs to be tested not assumed.

In the 1st and 2nd stages, the link between modelled climate data sets and outcomes is very clear. Modelled datasets that have poor results in quality control processes are readily identified. Also, runoff models typically use only 1-4 climate data sets, so poor results in the runoff quality control process can be linked to these data sets and issues resolved.

However, the quality control process for the 3rd stage for the river system model uses multiple climate and inflow data sets. In this case the link between a poor result and any individual climate data set is not so clear. Unless the results are poor across the board, the approach is to understand the results and develop the confidence that a result can be used to reliably inform a water management decision. The tests developed and implemented for this assessment were designed to provide that insight.

The statistical tests were based on comparing distributions derived by bootstrapping the instrumental data and the stochastic data. These distributions were compared graphically, and bias and skill metrics calculated to show respectively how close the medians of the distributions are, and how well the distributions overlap. The graphs and the metrics are reported in groupings of modelled outcomes: flows, storage levels, allocations, diversions, and environmental outcomes.

## Results

The flows metrics show low bias and high skill overall for system inflows and system outflows. From this we can have confidence that the major component of the river system water balance -inflows - is reliably modelled. In conjunction with the results at the end of system, this also provides indirect evidence by mass balance principles that the processes between the headwater inflows and the river outflows are also well represented. This flow result is in aggregated. However, the tests identify that even though the instrumental data is almost fully within the confidence limits, that there is a dry bias in the low flows.

The storage levels also have low bias and high skill overall, and this follows on from the corresponding results to the overall inflows. As the water stored is key to calculating water allocations and diversions, these are more likely to be well represented. However, the percent of time the storages have higher biases and lower skill, although the biases while high in relative terms, they are low in absolute terms as this only affects a small percent of days over the simulation period. While this does not affect allocations as much as the higher storage levels, these levels are more important for critical water decision-making which affect high security water users, and town water supplies.



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The results for diversions of all classes of entitlements have low bias and high skill, indicating that these results from the simulations using the stochastic data are similar statistically to the results using instrumental data. Apart from the inflows and the end of river, this is one of the large water balance components in the river system, so that the balance between inflows and outflows (including diversions) is overall statistically similar between simulations using instrumental data and the simulations using the stochastic modelled data.

Lastly, the results for environmental metrics were variable, but overall satisfactory, noting that these are not affected by the same inflows as reported in the earlier section, rather, by inflows downstream of the headwater storages, and are largely driven by medium sized rainfall events.

## Uncertainty and decision making

Models and data are often discussed as to whether they are fit for purpose as if this is a binary answer, i.e. they are, or that they are not fit for purpose. This assessment may be based for example on an arbitrary threshold of a performance indicator (e.g., Nash-Sutcliffe and bias). The fitness for purpose question and response is more nuanced, that the performance indicators are relevant to the outcome being assessed, and that the ‘fitness’ be considered a continuum rather than a threshold. The question is better posed as how fit for purpose is it for a particular policy or planning assessment (e.g., changes in flow thresholds for supplementary access), and whether it is important that the answer is important in an absolute sense, which might be the case for these entitlement holders business decisions (e.g., how much water will I get on average over a 5-year period), or whether it is important in an absolute sense (e.g., what impact will policy ‘A’ have on frequency of cease to flow events greater than 10 days).

The absolute answer needs to be in the context of uncertainty from many sources and requires a discussion on what an answer provided means in on-the ground outcomes. The relative answer has a hierarchy of content; (1) direction of change > (2) range of change > (3) best estimate.

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# Conclusion

The report details the development and implementation of the third stage of quality control of the stochastically generated climate data where it is fully input to the river system model the department uses to inform water resource management related decision making. Noting that the changes that can be made affect many different outcomes within that river system, the quality control tests need be able to inform the robustness of the results at different locations, different time scales, and different parts of the allocation and flow regimes. Narrowly defined tests and statistical measures are at risk of not properly informing that robustness.

The development of informative statistical tests and the range of modelled outcomes provides several lines of evidence as to the model suitability for water management purposes. These assessments showed statistically similar outcomes for all metrics between using instrumental data or stochastically modelled data. The largest water balance components, i.e., inflows and outflows as well as storage levels were all modelled with high skill and low bias. The results did indicate a dry bias for low flows however, and this would need to be kept in mind when modelling focuses on outcomes driven by low flows.

The overall conclusion based on the high skill scores and low biases for most measures is that the model can be used with stochastically modelled climate data in with confidence to examine most water management outcomes. The results of the assessments in this report should be borne in mind when communicating uncertainty to decision makers into its use for different policy questions.

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# Appendix A: Bootstrap methods

## Stochastic data

The stochastic bootstrap accounts for the uncertainty introduced by separating the stochastic data into non-overlapping 130-year blocks. We split the data into 130-year replicates to account for the difference in length between the stochastic and observed data and allow for a 'like-versus-like' comparison.

However, splitting the data into replicates may reduce multi-decadal variability compared to the full paleo-dataset. For example, if stochastic year 130 falls in the middle of a long dry period, separating the data into blocks could underestimate dry extremes in the stochastic distribution. Similarly, the impact of multiple long wet or dry periods occurring in close succession will not be accounted for in the statistics.

The stochastic bootstrap (bootstrap without replacement) resamples the data into different 130-year periods by rearranging blocks of data based on the stochastic water year. To preserve some of the original paleo-stochastic variability, the data is resampled in blocks of 20 years. This is shown graphically in Figure 17.


Figure 12. Graphical representation of bootstrapping stochastic data to calculate uncertainty.

Bootstrapping is only used to calculate confidence interval around values calculated per 130-year replicate (e.g., cease to flow events); reshuffling the data does not affect the calculation of percentiles or exceedance curves.

## Observed data

We also use bootstrapping to create a distribution for observed metrics. This allows us to calculate the Perkins skill score for metrics that only have one value per 130 years (i.e., a single observed value). The bootstrapping method used for instrumental data is a true bootstrap, that is, a bootstrap with replacement. This means that when we randomly draw a block from the data, it remains in the dataset so that it can be chosen again. This is shown graphically Figure 18.

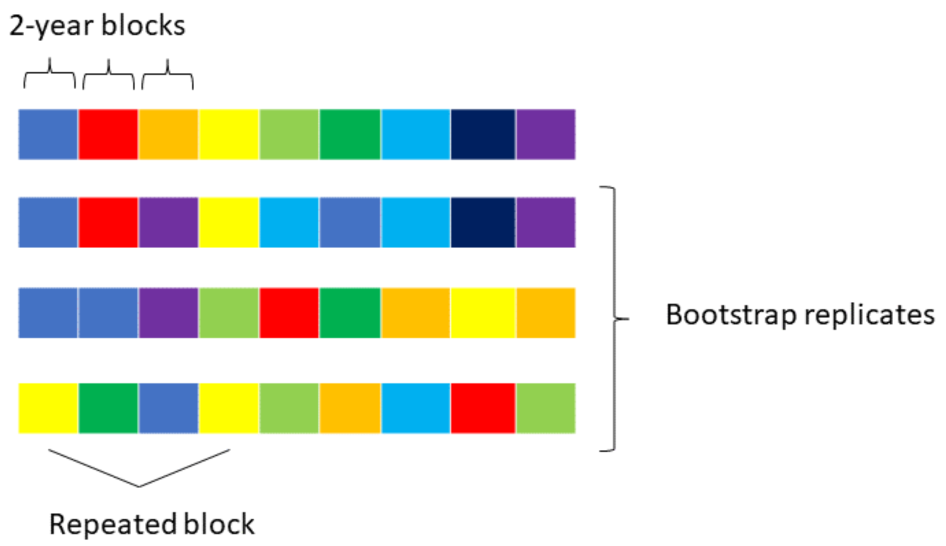


Figure 13. Graphical representation of bootstrapping instrumental data to calculate distributions.

We can consider the bootstrap to account for uncertainty in the observations. The central assumption is that our sampled data (the observations) accurately represent the actual population (the climate) but with a degree of error.

When we bootstrap the data, we draw random samples from the observations, assuming they are a proxy for the true population. The various combinations of values in the simulated samples collectively provide an estimate of the variability between random samples drawn from the same population.

Statistically, as the sample size increases, bootstrapping converges on the correct (population) sampling distribution under most conditions. Thus, we need to draw many more samples from the instrumental data than we do for the stochastic data.

## Appendix 4: List of documents provided to the Panel by DCCEEW for consideration in the Review

| | Document | Date received | Source |
|---|---|---|---|
| 1 | Assessment of non-stationarity in the northern basin | 25-Oct-24 | Publicly available |
| 2 | Assessment of non-stationarity for stochastic time series generation in the southern basin | 25-Oct-24 | Publicly available |
| 3 | Building the river system model for the Border Rivers Valley regulated river system | 25-Oct-24 | Publicly available |
| 4 | Climate datasets for assessing climate risk in regional water strategies – Volume 1: Design approach | 25-Oct-24 | Publicly available |
| 5 | Extraction limits: How the extraction limits work and differences | 25-Oct-24 | Publicly available |
| 6 | Extreme Events Policy: Policy framework for the management of NSW water resources during extreme events | 25-Oct-24 | Publicly available |
| 7 | Guidelines to select scenario models for assessing compliance to long-term average annual extraction limits | 25-Oct-24 | Publicly available |
| 8 | LTAAEL compliance assessment for NSW Border Rivers Regulated River Water Source | 25-Oct-24 | Publicly available |
| 9 | Floodplain harvesting entitlements for the NSW Border Rivers regulated river system: Model scenarios | 25-Oct-24 | Publicly available |
| 10 | Multisite rainfall and evaporation data generation for the Macquarie Valley | 25-Oct-24 | Publicly available |
| 11 | Namoi Source Model – Stakeholder engagement Workshops 1-4:<br>1. Modelling principles and objectives<br>2. Flows<br>3. Demands<br>4. Evaluation and reference scenarios | 25-Oct-24 | Not publicly available |
| 16 | Alluvium summary letter: Review of NSW Border Rivers Model Build, Scenarios and Environmental Outcomes reports relevant to Floodplain Harvesting Policy implementation | 25-Oct-24 | Publicly available |
| 17 | Water Allocation Methodology: Murrumbidgee Regulated River Water Source | 25-Oct-24 | Publicly available |
| 18 | Water Allocation Methods– NSW Border Rivers Regulated River Water Source | 25-Oct-24 | Publicly available |
| 19 | Technical review method: Minimum Inflows Review (October 2024) | 28-Oct-24 | Appendix 2 of this Review |
| 20 | Validating climate risk data for use in Border Rivers water sharing | 28-Oct-24 | Appendix 3 of this Review |
| 21 | Minimum Inflows Project – slide decks used as verbal briefings | 31-Oct-24<br>2-Dec-24<br>4-Feb-25 | Not publicly available |
| 22 | Economic Impact Assessment | 28-Nov-24 | Not publicly available |
| 23 | Environmental Impact Assessment | 28-Nov-24 | Not publicly available |
| 25 | eWater: Guidelines for rainfall-runoff modelling | 18-Feb-25 | Publicly available |

## Appendix 5: Department updates from 2020 OCSE Review

DCCEEW provided a formal response to the 2020 OCSE review containing commentary and an update on DCCEEW's progress on the recommendations. This can be found here. DCCEEW provided OCSE with a further update for the purpose of the present Review on what has been achieved since (update provided on 17 February 2025).

| No | Summary of Rec | Status | Date | Update 2025 (Dept) |
|---|---|---|---|---|
| 1 | Detailed documentation | In progress | Oct-23 | Still in progress - in draft form and expected to be published this year |
| 2 | Document reasons for choice of data source and quality assurance of observations | Completed | N/A | |
| 3.1 | Clarify references to ET and PET | Completed | N/A | |
| 3.2 | Consider replacing current PET approaches with physically based models | In progress | Dec-23 | First stage analysis completed, awaiting report from UNSW, non-stationarity review commissioned with Uni Melb |
| 4 | Collaborate to improve paleo records | In progress | Dec-23 | Data collection completed. Awaiting report from UoN |
| 5 | Collaboratively develop diagnostic principles for stochastic model performance | Completed | N/A | |
| 6.1 | Further explanation in the Methods report | Completed | N/A | |
| 6.2 | Further development of approaches to develop data where unclear of ?? | In progress | Ongoing | Expect this will remain on-going, information for report prepared for 6.3 may provide some guidance |
| 6.3 | Examine if future climate drivers' behaviours will remain consisten with past behaviours | Completed | N/A | Review report completed and published |
| 7 | Investigate stationarity to ensure that models do not underestimate climate risk | Completed | N/A | |
| 8 | Investigate impacts of parameter uncertainty in stochastic models on system yield | In planning | Ongoing | Project started, slated for completion May 2026 with reporting to NWGA in Sept 2026 |
| 9.1 | Incorporate NARCliM 1.5 into work | Completed | N/A | |
| 9.2 | Monitor approaches to ensure NSW the Methods remain at international standard | In progress | Ongoing | Ongoing, review process as part of Murray Darling Basin Plan Sustainable Yields 2 project provides some future guidance, and current work to integrate this data into water sharing plans shows evolution |
| 9.3 | Explore incorporation of NARCliM 2.0 | In planning | Jun-24 | Review process of and engagement with NARCLiM 2.0 is now in progress |
| 10 | Convene a state level community of practice | In progress | Ongoing | Community of practice established and convened through NSW Modelling and Monitoring Hub |