

# Independent Review of System Yield

WaterNSW Response to the Report

June 2026



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# 1. Introduction

WaterNSW uses the WATHNET model to determine system yield in accordance with the design criteria. WaterNSW has developed and maintains the WATHNET model of the Greater Sydney bulk water supply system. The WaterNSW Operating Licence requires an independent expert to review and report on the model and the modelling processes used to determine system yield. The independent review was conducted by HARC Services Pty Ltd in accordance with Clause 36 of the Operating Licence.

## 2. Purpose of this report

Under clause 36(4) of its Operating Licence, WaterNSW must submit a report by 30 June 2026, in accordance with the reporting manual that:

- attaches the independent expert's report
- includes WaterNSW's response to the review findings including opportunities for improvement that WaterNSW proposes to action, by when and the anticipated cost to do so,
- identify opportunities for improvement that WaterNSW does not propose to action and reasons for this,
- and explain how the review considered stakeholder input collected under clause 36(3)

This report provides details on the stakeholder consultation undertaken for the project, how the feedback was incorporated into the review and WaterNSW's response to the final recommendations contained in the attached WATHNET Independent Review 2026 Final Report (WaterNSW Document Reference D2026/37155).

# 3. Stakeholder Consultation

## 3.1 Consultation Strategy

WaterNSW commenced early stakeholder consultation for the independent yield review project in September 2025, consistent with the requirements of Clause 36 of the WaterNSW Operating Licence.

A Stakeholder Management Plan was developed by the project team to identify relevant stakeholders and establish an appropriate communication and engagement strategy. This plan was shared with IPART and refined to ensure alignment with regulatory expectations and to support effective stakeholder participation throughout the review process.

Stakeholders identified for participation in the yield review included those specified in the Operating Licence - IPART, Sydney Water, and the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW), as well as a broader group comprising commercial entities, local water utilities, environmental organisations, direct customers (via established Customer Advisory Group frameworks), and academic organisations engaged through the expert panel workshop. A dedicated project mailbox was established which was shared with stakeholders as part of engagement activities to enable stakeholders to directly contact the project team.

WaterNSW presented an overview of the yield review project to the Greater Sydney Customer Advisory Group (CAG) on 18 September 2025. This session outlined the scope and objectives of the review and invited stakeholders to submit expressions of interest to participate or request further information.

Targeted early consultation sessions were also conducted with IPART, DCCEEW, and Sydney Water. These engagements focused on confirming the project scope and objectives, identifying stakeholder representatives, and establishing data requirements and assumptions. In December 2025, WaterNSW presented to the Water Services Association of Australia (WSAA) Bulk Water Network, an industry forum comprising major water utilities from around Australia to inform participants of the review and invite collaboration from organisations with expertise or interest in bulk water supply modelling.

The project scope of works was structured to incorporate stakeholder input at the earliest practicable stage. This approach ensured that the independent reviewer could consider stakeholder perspectives and requirements during both the technical review stage and the development of recommendations. After a competitive selection process, HARC Services Pty Ltd was formally engaged as the independent reviewer in January 2026.

A stakeholder workshop was held on 24 February 2026 at WaterNSW's Parramatta office, with hybrid participation via Microsoft Teams. The workshop was facilitated by HARC and provided an overview of the review methodology, objectives, and program. It also enabled stakeholders to seek clarification and provide input regarding the scope, process, and desired outcomes of the review.

Stakeholders were invited to submit written feedback directly to the project mailbox and HARC review team to ensure that all inputs were formally captured prior to the commencement of the technical review. Written submissions were received from Sydney Water and NSW Treasury. In addition, targeted consultation sessions were subsequently conducted between HARC, WaterNSW, and key agencies including Sydney Water, DCCEEW, and NSW Treasury.

## **3.2 Incorporation of Stakeholder Feedback into the review**

The importance of stakeholder consultation was explicitly outlined within the project scope of works to ensure that feedback was captured, assessed, and meaningfully incorporated into the review process.

The scope required the independent reviewer to:

- Ensure that feedback from relevant stakeholders with an interest in the determination of system yield was appropriately considered;
- Facilitate a stakeholder workshop with WaterNSW and stakeholders to communicate the review scope, methodology, and timeline, and to provide an opportunity for stakeholder input; and
- Conduct the workshop within an early timeframe (3–4 weeks from contract award) to enable stakeholder feedback to be incorporated into the review.

Key themes arising from stakeholder feedback included:

- The need for enhanced articulation of model assumptions, outputs, capabilities, and limitations; to support improved stakeholder understanding of model capability
- A desire for extended modelling capability beyond the bulk water supply system to represent downstream constraints, including network, distribution, and treatment limitations;
- Consideration of alternative or supplementary water security metrics and design criteria; and
- Improved access to model outputs to support best-practice asset management, particularly for commercial stakeholders.

Records of the stakeholder workshop and all written submissions were provided to the expert review panel to ensure that stakeholder perspectives were explicitly considered during the assessment of preliminary

findings. Stakeholder feedback has directly informed both the expert panel's review conclusions and several of the resulting recommendations.

To ensure all feedback was acknowledged and considered, HARC have documented all stakeholder feedback as received, including identification of matters that were outside the formal scope of the technical review (which was focused on the WATHNET model, processes and associated input datasets).

It is noted that some recommendations arising from stakeholder input extend beyond the immediate scope of the technical review and will require broader cross-agency consultation, resourcing, and policy alignment. In particular:

- Recommendations relating to demand assumptions and demand-side policy will require collaboration with Sydney Water; and
- Recommendations regarding design criteria, operating licence settings, and broader policy considerations will require engagement with NSW DCCEEW.

# 4. WaterNSW's response to the Yield Review Report

## 4.1 Summary of Recommendations and WaterNSW response

HARC has identified approximately 120 recommended actions in the review report which have been consolidated into 33 overarching recommendations, of which 26 recommendations relate to modelling aspects for which WaterNSW has responsibility. Table 1 summarises these 26 recommendations from the independent review, along with WaterNSW's response to each recommendation.

In general, WaterNSW supports the intent of the independent review recommendations and proposes to progress the recommendations relevant to its responsibilities, subject to further investigation, prioritisation, funding availability and confirmation that proposed changes are suitable for the Greater Sydney system and represent value for money in line with customer expectations. WaterNSW has already completed or commenced several actions and will prioritise higher-impact recommendations that are most likely to improve model robustness, transparency and confidence in system yield estimates.

WaterNSW notes that many of the recommendations are investigative in nature based upon the reviewer's understanding of WaterNSW modelling and industry practice across Australia. It is noted that several of the recommendations here had previously been investigated by WaterNSW, with the impacts found to be immaterial, the state of practice not mature, or the case for deviation away from practice not material to warrant the change. Other recommendations, however, are new recommendations or updating of previous recommendations that reflect good practice.

For the remaining 7 of 33 consolidated recommendations: these rely on external policy settings, demand assumptions, distribution network information or broader regulatory considerations, WaterNSW supports further consideration in principle and will work with Sydney Water and NSW DCCEEW where their input or leadership is required. These recommendations are summarised in Table 2. Additional detail, including specific actions included under each recommendation are outlined in the attached report.

## 4.2 Estimated time and cost to implement recommendations

Section 8.2.1 of the WaterNSW Reporting Manual requires that the system yield review report outline the anticipated costs associated with the proposed actions, as well as the expected timeframe for their implementation. As discussed above, WaterNSW generally proposes to implement all 26 recommendations relevant to its responsibilities, subject to confirmation of their suitability through further investigation and available funding.

**WaterNSW estimates the total cost of the program to investigate and implement, test, and embed in systems and processes all the recommendations from the independent expert review report to range from \$2.5 M- \$4 M.** A further detailed cost breakdown has not been provided in this report due to commercial sensitivity. It is noted that this estimate is preliminary and based on high-level assumptions regarding the required level of effort, timing, and resourcing approaches. WaterNSW notes that there remains a potential for significant variation as further scoping and detailed planning is undertaken.

**To ensure prudent and efficient expenditure, WaterNSW will prioritise the recommendations,** working within funding constraints, and in alignment with our assessment of materiality and priority, as listed in Table 1. Several actions have already commenced, been completed or considered for a future work plan.

The proposed implementation timeframes in Table 1 should likewise be considered indicative only. Timeframes will be refined as part of detailed scoping, prioritisation, and feasibility assessments, including consideration of inter-agency dependencies and resource availability.

WaterNSW also notes that a number of recommendations are expected to require substantial input, coordination, and resourcing from external agencies, including Sydney Water and the NSW DCCEEW. At this stage, it is not feasible to quantify the total cost associated with these externally dependent components.

**Table 1- Summary WaterNSW Recommendations and response**

Recommendation	Category	WaterNSW Position	WaterNSW Response and Proposed action	Likelihood of Impacting Yield Value	Priority	Estimated Timeframe (subject to funding)
<b>1. Develop and maintain documentation of input data and model development</b>	Documentation and Auditability	Agree	WaterNSW accepts this recommendation to further develop and maintain documentation relating to the WATHNET model. Existing model documentation will be improved as part of future model refinements - with ongoing documentation occurring throughout the period of implementation.	Low	Medium	End 2030
<b>2. Use gauged rainfall for deriving streamflow where possible unless gridded rainfall is the only available source of data and its use can be validated</b>	Input Data Methodology	Partially Agree	WaterNSW accepts to investigate the use of gauged rainfall data where available and applicable over gridded rainfall datasets. Investigations of availability and confirmation of the change will be documented.	Medium	Medium	End 2028
<b>3. Undertake statistical testing for climate non-stationarity and non-climatic trends in hydroclimate data and appropriate de-trending for use in water resources modelling and climate change impact assessment</b>	Input Data Methodology	Partially Agree	WaterNSW has commenced analysis for climate non-stationarity as part of the NARCLIM 2.0 Climate Change Assessment on System Yield Project. WaterNSW acknowledges literature proposing available techniques exists, however further investigations will be required in relation to this recommendation.	Medium	Medium	End 2028

<p><b>4. Investigate and adopt estimates of lake evaporation using Morton-based methods, with consideration of deep lake evaporation for reservoirs deeper than 30 m were found to be suitable</b></p>	<p>Input Data Methodology</p>	<p>Partially Agree</p>	<p>WaterNSW has undertaken preliminary analysis using the Morton based methods as part of this review. If found to be suitable WaterNSW will use the revised evaporation for inflow derivation and in the WATHNET model.</p>	<p>Medium</p>	<p>Medium</p>	<p>End 2027</p>
<p><b>5. Review and update historical inflow estimates where appropriate</b></p>	<p>Input Data Methodology</p>	<p>Partially Agree</p>	<p>WaterNSW will review historical inflow estimates. WaterNSW notes that this recommendation is heavily dependent on the recommendation to develop suitably calibrated rainfall-runoff models for yield estimation.</p>	<p>Medium</p>	<p>Medium</p>	<p>End 2029</p>
<p><b>6. Develop rainfall-runoff models that are calibrated using appropriate objective functions for water security assessment for historical inflow estimation and climate change impact assessment.</b></p>	<p>Model Review and Updates</p>	<p>Agree</p>	<p>WaterNSW accepts this recommendation and will investigate available rainfall-runoff models and development techniques to confirm suitability for water security assessment.</p>	<p>High</p>	<p>High</p>	<p>End 2029</p>
<p><b>7. Review stochastic data generation methodology</b></p>	<p>Input Data Methodology</p>	<p>Agree</p>	<p>WaterNSW accepts this recommendation as recent advances in understanding of past and future climate warrants a review of approaches. WaterNSW has commenced analysis into several recommendations relating to the stochastic data generation approach. The CPAG direction to adopt RWS paleo datasets will lead to inconsistencies in deriving inputs due to the lack of a temperature data set available. Paleo datasets have not been tested thoroughly by WaterNSW, and WaterNSW has not been involved in the development of the Paleo datasets for Greater Sydney. The expert panel workshop and subsequent</p>	<p>High</p>	<p>High</p>	<p>End 2027</p>

			<p>discussions with respected experts have identified that better data and techniques to assess driving mechanisms may be available for the Greater Sydney context – WaterNSW intend to explore the opportunities here in conjunction with NSW DCCEEW and academic partners prior to formally implementing the existing paleo sets. WaterNSW notes that assessment and adoption of alternative stochastic models to the widely adopted and longstanding approach of generating annual flow using the AR1 model is a major change to the yield assessment methodology and may require extensive investigations.</p>			
<p><b>8. Develop framework for appropriate checks of climate model outputs and undertake those checks</b></p>	<p>Climate Change Yield Modelling</p>	<p>Agree</p>	<p>WaterNSW has undertaken evaluation of the climate model outputs as part of the NARCLIM 2.0 Climate Change Assessment on System Yield Project. Clear prescription of reporting metrics and modelling performance targets is not currently available at this time. WaterNSW will develop this framework as its practice becomes established. It is anticipated that the interagency Climate Change Technical Working Group will be engaged on this to determine the appropriate checks and guidance consistent across NSW where suitable. WaterNSW will undertake further investigations in relation to this recommendation.</p>	<p>Medium</p>	<p>High</p>	<p>Mid-2027</p>
<p><b>9. Implement outlet and transfer capacity constraints within arcs, scripts and system tables</b></p>	<p>Minor Model Updates</p>	<p>Partially Agree</p>	<p>WaterNSW will review and update the model elements where required and appropriate. Historically, where monthly constraints have not been an issue or reached, they have not been inserted in scripts for simplicity.</p>	<p>Low</p>	<p>Low</p>	<p>End 2026</p>

<b>10. Reconcile Water Sharing Plan environmental flow release values and undertake check rules are up to date and incorporated correctly</b>	Minor Model Updates	Agree	WaterNSW has implemented this recommendation as part of the review.	Complete	Complete	Complete
<b>11. Undertake WATHNET Greater Sydney System model calibration &amp; validation</b>	Model Review and Updates	Agree	WaterNSW will undertake the historical model calibration and validation at a suitable time following the investigations and implementation of the high priority actions from the review. WaterNSW notes this action is contingent on completion of the actions relating to rainfall and evaporation input data in addition to the model updates.	Low	Low	End 2029
<b>12. Check and if necessary, update representation of total and active storage in model</b>	Minor Model Updates	Agree	WaterNSW has implemented this recommendation as part of the current review. WaterNSW notes that the new Version 6 of the WATHNET software will include updates on how total and active storage is represented in the model and may require subsequent model refinement.	Complete	Complete	Complete
<b>13. Adopt consistent hydroclimate data sets and assumptions for inflow derivation, stochastic data generation, and for simulation</b>	Input Data Methodology	Partially Agree	WaterNSW will review historical inflow estimation techniques currently utilised, and cross check against model input data sets to analyse abnormalities or numbers that require adjustment, either within the historical sets or the model itself, where appropriate.	Medium	High	End 2027

<p><b>14. Check relationship between historic inflows/climate and historic seasonal fraction used for demand is maintained in the stochastic data. If required derive a relationship as a function of climate to determine climatic factors for use in synthetic runs</b></p>	<p>Input Data Methodology</p>	<p>Agree</p>	<p>WaterNSW has commenced analysis for recommendation as part of the review project.</p>	<p>High</p>	<p>Medium</p>	<p>Mid- 2027</p>
<p><b>15. Check performance of harvest node versus proxy equations under climate change</b></p>	<p>Minor Model Updates</p>	<p>Agree</p>	<p>WaterNSW will review the performance of the harvest node under climate change scenarios. WaterNSW has undertaken previous comparisons between equation methods and the harvest node, with the decision made to retain equation methods due to relatively minor changes resulting in the downside of inconsistent numbers between runs. WaterNSW's current preference is to use the equation method rather than the harvest node due to issues reproducing results with harvest node methodology.</p>	<p>Low</p>	<p>Low</p>	<p>End 2027</p>
<p><b>17. Revise calibration of water values and arc penalties for current base model conditions</b></p>	<p>Model Review and Updates</p>	<p>Agree</p>	<p>WaterNSW will endeavour to undertake a revision of the water values as a priority action item, noting that recalibration of the water values is likely to be a significant undertaking. Hard coding of Upper Nepean rules in 2025 are an example of works undertaken to facilitate consistency in shortfalls. Whilst the reviewer (Kuczera) acknowledged 2025 work was fit for purpose, WaterNSW agree with recommendation to revisit water values to maintain the long-term robustness of the model.</p>	<p>High</p>	<p>High</p>	<p>End 2029</p>

<b>20. Model scripting updates to improve transparency</b>	Minor Model Updates	Agree	WaterNSW will review and update the model elements where required and appropriate as part of ongoing development and practice and in line with Recommendation 1.	Low	Low	Mid- 2027
<b>21. Report on exceedance of respective Long-Term Average Annual Extraction Limits in model</b>	Minor Model Updates	Agree	WaterNSW will review and update the model elements where required and appropriate.	Low	Low	End 2026
<b>24. Remove redundant scripts and arcs</b>	Minor Model Updates	Agree	WaterNSW will review and update the model elements where required and appropriate.	Low	Low	End 2027
<b>25. Investigate, and if found to be suitable for the Greater Sydney region, undertake climate change projection and scaling methods using alternative approaches, including co variate analysis and pattern scaling</b>	Climate Change Yield Modelling	Agree	WaterNSW will continue to develop its approaches to climate change impact assessment in response to the review recommendations. WaterNSW notes that this recommendation is in part contingent on successful completion of the recommendation relating to the development of rainfall runoff models.	Medium	High	End 2030
<b>26. Investigate changing rainfall-runoff response due to extended drought or climate change</b>	Climate Change Yield Modelling	Partially Agree	WaterNSW has undertaken initial research work following the 2021 review, partnering with the University of Newcastle to undertake a project to prototype vegetation-aware rainfall runoff models, with mixed results. Further research and testing of approaches to investigate this recommendation will likely require significant external support through academic or industry partners and will be considered under WaterNSW's Research program.	Medium	Medium	End 2030

<b>28. Update Sydney Nodal demand distribution</b>	Minor Model Updates	Agree	WaterNSW has implemented this recommendation as part of the review.	Complete	Complete	Complete
<b>29. Make arc specific edits to key transfer infrastructure and associated operating rules</b>	Minor Model Updates	Agree	WaterNSW will review and update the model elements where required and appropriate.	Low	Low	Mid- 2027
<b>30. Justify equations in documentation and scripts including daily to monthly conversion factors</b>	Documentation and Auditability	Agree	WaterNSW will review existing legacy model documentation and include the relevant information in future documentation.	Low	Medium	End 2027
<b>31. Improve robustness of model and yield modelling process</b>	Documentation and Auditability	Partially Agree	<p>This recommendation relates to a range of improvements to add further details on how the model theoretically reflects the operational environment of Greater Sydney water Supply system 'reality' in the model. It does not refer to the technical term "model robustness" as it relates to ability of a model to produce reliable, stable, and consistent outputs.</p> <p>WaterNSW has commenced implementing aspects of this recommendation and will continue to review and update the model elements where required and appropriate. WaterNSW notes that some recommendations relate to refinements to the structure of scripting that will require significant effort and will be influenced by the future development of the WATHNET software.</p>	Medium	Medium	End 2029
<b>33. Recommendation to retain and continue a business-as-usual activity relating to climate change impact analysis and yield analysis</b>	N/A	Agree	No action required, current practice	N/A	N/A	N/A

**Table 2- Recommendations which require external organisation support**

Recommendations for further consideration	WaterNSW Response
<p><b>16. Confirm local inflows and losses do not need to be represented under either current or future climate</b></p>	<p>Residual catchment runoff factors derived from DCCEEW rainfall-runoff models have been incorporated; however, WaterNSW will consult with the NSW DCCEEW Water Modelling Group to confirm whether additional representation of local inflows and losses is warranted under current and future climate conditions.</p>
<p><b>18. Improve representation of infrastructure and resolution of the representation of bulk water supply and distribution network to capture local constraints</b></p>	<p>WaterNSW supports this recommendation in principle and will collaborate with Sydney Water to investigate the development and testing of a higher-resolution representation of demand zones and the distribution network, subject to feasibility and data availability.</p>
<p><b>19. Confirm that the current and future impact of diversions and interception activities is negligible</b></p>	<p>WaterNSW will seek advice from the NSW DCCEEW Water Modelling Group, as the lead agency in this area, to confirm the significance of diversions and interception activities in downstream reaches and whether their inclusion in modelling is required.</p>
<p><b>22. Consider alternative demand and restriction modelling approaches</b></p>	<p>WaterNSW supports further investigation of alternative approaches and will work in consultation with Sydney Water and NSW DCCEEW, as the lead agencies for restriction policy, to assess and implement revised approaches where demonstrated appropriate.</p>
<p><b>23. Consider the impact of water quality on bulk supply and if required explore options to represent them with proxy variables</b></p>	<p>This was discussed as outside of scope, however consideration of water quality impacts on water availability are addressed elsewhere within other modules of WATHNET and additional WQ modelling tools and are part of ongoing discussions between Sydney Water, DCCEEW and WaterNSW.</p>
<p><b>27. Consider utilising one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs</b></p>	<p>WaterNSW will seek guidance through the NSW Government Climate Change Technical Working Group, cognisant of the <i>TPG23-17 Disaster Cost-Benefit Framework</i>, on the appropriate incorporation of such scenarios into modelling frameworks.</p>
<p><b>32. Investigate alternative or revised design criteria, drought reserve policy concepts, and independent review scope.</b></p>	<p>It is NSW DCCEEW Water’s responsibility to set the design criteria and Greater Sydney Drought Response Plan. In that regard, the <i>Greater Sydney Water Strategy Implementation Plan</i> raises specific actions to investigate levels of service and assumptions. WaterNSW will work closely with NSW DCCEEW and Sydney Water, where appropriate within the regulatory setting, to investigate and advise options and potential changes to design criteria, risk appetite statements and metrics, drought reserves and other matters going forward.</p>

# **Attachment 1 - Independent Review Report**



## **WATHNET Model Independent Review 2026**

### **Project Report**

**Final**

**24 June 2026**

## Document status

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Stakeholder workshop participants:

- NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) – Mohammad Mortazavi-Naeini, Simon Williams, Rachel Watson
- Sydney Water – Paul De Sa, Jonathan Dixon, Lydia Aristuti, Marcia Dawson, Karen Chia
- Independent Pricing and Regulatory Tribunal NSW (IPART) – Shweta Shrestha, Robert Aposhian
- WaterNSW – Allen Lal, Bede Johnston, Angelo Breda, Lorena Oliveira, Michelle Zhang
- HARC – Kate Austin, Stephanie Kermode, Phillip Jordan, Brad Neal
- Wingecarribee Shire Council – Om Malla, Graeme Mellor, Clinton McAlister
- Sydney Desalination Plant – Matt Blaikie, Iftekhar Omar
- Goulburn Mulwaree Council – Marina Hollands, Trevor Sultana
- NSW Treasury – Peter Leventis, Sarah Wong, Rassam Moshrefi
- Shoalhaven City Council – DJ Dubose
- Melbourne Water – Tim Hatt, KS Tan, Udaya Kularathna

Expert Panel members:

- KS Tan (Melbourne Water)
- Tim Purves (Icon Water)
- Brendan Berghout (Hunter Water)
- Emeritus Professor George Kuczera (University of Newcastle)
- Associate Professor Anthony Kiem (University of Newcastle)

## Executive Summary

### E.1 Overview of approach

Under Clause 36 of the WaterNSW Operating Licence 2024–2028, WaterNSW is required to engage an independent expert to review its model, modelling and processes for determining system yield. The review is required to:

- Ensure the modelling framework is robust and reflects good industry practice.
- Identify opportunities for improvement in model structure, assumptions, and yield estimation methodology.
- Consider stakeholder feedback, including from Sydney Water, IPART, and other relevant agencies.
- Be completed and reported to IPART by 30 June 2026.
- Include WaterNSW's response to the expert's findings, outlining which recommendations will be adopted and why.

The phases of the project were:

- Collection of background information and stakeholder input via a workshop, meeting and written responses from stakeholders.
- The preparation of three separate review reports covering (a) hydrology (b) the WATHNET model and yield modelling approach, and (c) the approach to climate change modelling.
- Review of those three reports by the Expert Panel, including a workshop with the Expert Panel to discuss the key findings.
- Incorporation of expert panel comments into a consolidated review report.
- Review of the consolidated review report by WaterNSW.
- Finalisation of the consolidated review report, taking into account feedback from WaterNSW. This report documents the model review, stakeholder feedback, expert panel findings and includes recommendations for future enhancement

### E.2 Review of historical & stochastically generated hydrology data

#### E.2.1 Historical hydrology data

It is recognised that the datasets for use in water resources modelling for Greater Sydney have been continually developed, updated, and periodically reviewed since the 1990s and have been found to provide a sound basis for estimating yields. In this review, HARC has identified a number of opportunities to potentially improve the derived historical inflows for estimating yield. These include quality checking climate data for non-climatic signals, and revisiting rainfall-runoff model calibration objectives and calibration strategies.

HARC also recommends that documentation on the data sources be developed and/or maintained to ensure transparency in approaches and assumptions, and to underpin decisions with respect to the adopted methods both retrospectively as well as into the future. This includes documentation of assumptions, methods and outcomes where previous reviews have made recommendations that have been implemented or are in the process of being implemented.

## E.2.2 Synthetic inflows

HARC concludes, in line with previous reviews, that the method for generating synthetic inflow using the stochastically generated annual (calendar year) data from an AR1 model and disaggregated to monthly data using a non-parametric k-nearest-neighbour approach is fit for the purpose of yield estimation. The suitability of the synthetic data is, however, dependent on the data used to calibrate the model and HARC recommends the assessment of the input historical data for non-climatic signals.

HARC identified that the current implementation of the non-parametric disaggregation using a parameter value of  $k = 1$  (relative to using higher k-values) will result in decreased variability in monthly temporal patterns for years where simulated values are near to, or exceed, the bounds of the historical data. This is particularly relevant for simulated dry inflows that will impact on system metrics of reliability and security. We recommend the use of a value of k of up to  $\sqrt{N}$  where N is the number of observed years, consistent with WATHNET guidance, and accompanied by an investigation of whether the selected years are climatically similar to the simulated year.

NSW DCCEEW's Regional Water Strategy paleo-stochastic datasets on the NSW Government's online SEED database were adopted in late 2025 as a NSW Treasury Common Planning Assumption. However, those online datasets do not currently include sites in the Greater Sydney region. If this Common Planning Assumption were to apply to the Greater Sydney region in future, it is expected that it would take time and effort for WaterNSW to align its methods with this assumption, particularly given the longer stochastic datasets and different climate variables currently required by WaterNSW, relative to those available from the Regional Water Strategy data generation process.

## E.3 Review of the climate change impact on system yield analysis

Incorporating climate change impacts into the calculation of yield is a new requirement for WaterNSW under its 2024-2028 Operating Licence. Under Clause 35(2) of the licence WaterNSW must conduct its activities in a manner that considers the impacts of climate change when it is determining or re-determining the system yield (IPART, 2024).

From our review HARC concludes that the climate change impact assessment undertaken in 2023 for the Long-Term Capital and Operational Plan was fit-for-purpose, reflecting contemporary good practice at the time of that assessment. The assessment included WaterNSW documentation on methods, assumptions, their justification, and quality control/assurance checks.

It is difficult for HARC to fully assess the suitability of WaterNSW's 2026 climate change impact assessment methods and assumptions because those methods are currently being developed and applied, and have not yet been documented. The review recommendations provided by HARC on the 2026 methods offer an opportunity for WaterNSW to consider and adapt its methods as they are implemented. HARC understands that WaterNSW has commenced this process, based on HARC's draft report findings.

Opportunities for WaterNSW include to continue to test recent innovations in climate change impact assessment methods (i.e. temperature co-variate analysis and pattern scaling) with the aim of transitioning to improved methods where they are demonstrated to provide benefits locally.

WaterNSW's ongoing collaboration with other agencies will help to achieve consistency in climate change assumptions across NSW Government stakeholders where it is reasonable to do so. This includes ongoing participation in DCCEEW's metropolitan climate change working group, continued

alignment with NSW Treasury's Common Planning Assumptions for climate change, and continued sharing of climate change impact assessment assumptions and methods with Sydney Water and other stakeholders.

WaterNSW's current practice of analysing and providing guidance on the full range of yield estimates from all NARCIIM2.0 projections, rather than focussing on only a single climate future, is supported by HARC as important for underpinning assessments of supply system robustness to future climate uncertainty. Revisiting rainfall-runoff model calibrations would also be of benefit to WaterNSW's climate change impact assessment, in addition recommending this for HARC's historical hydrology data review above.

## **E.4 Review of the WATHNET model and yield calculation approach**

The WATHNET model and yield modelling approach was reviewed, paying particular attention (but not limited to) changes made to the model since the 2021 review, implementation of recommendations from the 2021 Model Review (WREMA, 2021) and implementation of recommendations from the 2025 Interim Review (Kuczera, 2025).

Recommendations included various essential checks, corrections and potential model enhancements, followed by model calibration and verification of the model to confirm it is fit-for-purpose for yield assessment. It was also recommended that historic and ongoing model development and the basis of all model assumptions be fully documented.

The WATHNET review found that the current steady state approach to modelling yield is appropriate, subject to the completion of essential checks, corrections and enhancements.

Discussion of alternative water resource modelling assessment techniques in addition to steady-state yield analysis is included in the body of the report.

## **E.5 Summary of recommendations**

Specific recommendations have been subjectively classified by HARC in the body of the report by their relative level of effort (low, medium, high) and prioritised (low, medium, high) based on their potential impact on model accuracy and/or estimates of yield. For the purposes of clarity and to support WaterNSW's implementation of the recommendations, the approximately 120 recommended actions described by HARC in the body of the report have been grouped into 33 categories. These are listed in Table 8-1.

Implementing the recommendations will improve the clarity and defensibility of WaterNSW's methods and in some cases could impact on yield estimates. Implementing these recommendations will ensure that WaterNSW addresses the WaterNSW Operating Licence 2024-2028 obligations regarding reporting, record keeping, and ease in providing information. This includes improved documentation of quality control checks, investigations, and model performance

The priority for implementation of recommendations will be a matter for WaterNSW. HARC has however indicated in Table E-1 those individual recommendations considered in the review to be higher priority to correct an error or omission, to check and justify existing assumptions, or where the recommendation could have a material impact on supply system yield or the implementation of downstream tasks.

Some recommendations, even if higher priority, are not low effort and may take some time (many months, not days or weeks) to implement. Recommendations which are investigative in nature, or require collaboration with other stakeholders, may also take longer to implement than other recommendations.

WaterNSW have also advised that implementation of some recommendations has already occurred between the delivery of HARC's draft report and this final report, with those recommendations also highlighted in Table E-1. The verification by HARC of actions implemented by WaterNSW since the issue of the draft report was not part of this review.

**Table E-1: Summary of recommendations grouped by theme. Suggested higher priority recommendations are highlighted in red. Recommendations already implemented by WaterNSW between the draft and final review report are highlighted in green.**

Group number	Description	Individual recommendations (red = higher priority, green = already implemented by WaterNSW)
1	Develop and maintain documentation of input data and model development	H1, H2, H5, H6, H9, H10, H11, H12, H21, H22, CC14, CC20, CC22, <b>W24, W25</b> , W56, W57, W58, W59, W60, W61
2	Use gauged rainfall for deriving streamflow where possible unless gridded rainfall is the only available source of data and its use can be validated	H3, CC2
3	Undertake statistical testing for climate non-stationarity and non-climatic trends in hydroclimate data and appropriate de-trending for use in water resources modelling and climate change impact assessment	<b>H4, H8, CC1</b>
4	Investigate and adopt estimates of lake evaporation using Morton-based methods, with consideration of deep lake evaporation for reservoirs deeper than 30 m where found to be suitable	H7
5	Review and update historical inflow estimates where appropriate	<b>H13</b> , H14, <b>H18</b> , H23, H27
6	Develop rainfall-runoff models that are calibrated using appropriate objective functions for water security assessment for historical inflow estimation and climate change impact assessment.	<b>H15, H16, H17</b> , H19, <b>H20, CC4</b>
7	Review stochastic data generation methodology	<b>H24, H25, H26, H28, H29, H30</b> , H31, <b>H32</b>
8	Develop framework for appropriate checks of climate model outputs and undertake those checks	<b>CC7</b> , CC12, CC13
9	Implement outlet and transfer capacity constraints within arcs, scripts and system tables	<b>W1</b> , W36
10	Reconcile Water Sharing Plan environmental flow release values and undertake check rules are up to date and incorporated correctly	<b>W3</b> , W4, W54
11	Undertake WATHNET Greater Sydney System model calibration & validation	<b>W6, W7</b>
12	Check and if necessary update representation of total and active storage in model	<b>W8, W26, W29</b> , W30, W31
13	Adopt consistent hydroclimate data sets and assumptions for inflow derivation, stochastic data generation, and for simulation	<b>W9, W10</b>
14	Check relationship between historic inflows/climate and historic seasonal fraction used for demand is maintained in the stochastic data. If required derive a relationship as a function of climate to determine climatic factors for use in synthetic runs.	<b>W11</b>
15	Check performance of harvest node versus proxy equations under climate change	W12, W13, W21

Group number	Description	Individual recommendations (red = higher priority, green = already implemented by WaterNSW)
16	Confirm local inflows and losses do not need to be represented under either current or future climate	W16, W27
17	Revise calibration of water values and arc penalties for current base model conditions	W14, W15, W55
18	Improve representation of infrastructure and resolution of the representation of bulk water supply and distribution network to capture local constraints	W16, W17, W65
19	Confirm that the current and future impact of diversions and interception activities is negligible	W28
20	Model scripting updates to improve transparency	W32, W34, W35, W37, <b>W40</b> , W43, W45, W46, W47, W48, W50
21	Report on exceedance of respective Long-Term Average Annual Extraction Limits in model	W33
22	Consider alternative demand and restriction modelling approaches	W22, W38, W66, W68, W69, W70
23	Consider the impact of water quality on bulk supply and if required explore options to represent them with proxy variables	W42
24	Remove redundant scripts and arcs	W44, W53
25	Investigate, and if found to be suitable for the Greater Sydney region, undertake climate change projection and scaling methods using alternative approaches, including co variate analysis and pattern scaling	CC8, CC15, <b>CC16</b> , <b>CC17</b> , CC18, CC19
26	Investigate changing rainfall-runoff response due to extended drought or climate change	CC5, CC6
27	Consider utilising one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs	CC21
28	Update demand distribution	<b>W2</b>
29	Make arc specific edits to key transfer infrastructure and associated operating rules	W18
30	Justify equations in documentation and scripts including daily to monthly conversion factors	W19, W20
31	Improve robustness of model and yield modelling process	<b>W5</b> , W23, W39, W41, W49, W51, W52, W71
32	Investigate alternative or revised design criteria, drought reserve policy concepts, and independent review scope	W64, W67, W72
33	A recommendation to retain and continue a business as usual activity	<b>CC3</b> , <b>CC9</b> , <b>CC10</b> , <b>CC11</b> , <b>W62</b> , <b>W63</b>

# 1. Introduction

## 1.1 Context for the WATHNET Model

### 1.1.1 Calculation of yield

The WaterNSW Operating Licence 2024-2028 requires WNSW to use a long-term hydrological model to determine the amount of water (Yield) it can supply from water sources within declared catchment areas subject to the system design criteria (IPART, 2024).

The current design criteria are provided by the minister and published on WaterNSW's website<sup>1</sup>:

- Security: The probability of the total system storage falling to 5% should be less than 1:100,000 months.
- Robustness: Restrictions should not occur more frequently than 1:10 years on average.
- Reliability: Restrictions should not occur more frequently than 5% of months on average.

The system yield is the maximum amount of water that can be extracted whilst satisfying the design criteria. The System Yield or Performance of water supply system is currently evaluated using WATHNET, a generalised simulation and optimisation model. The system yield is calculated using stochastic replicates generated using historical monthly inputs from 1909 to 2024.

### 1.1.2 Greater Sydney Supply System

WaterNSW supplies raw water for treatment and distribution by Sydney Water. The Sydney Desalination Plant (SDP) supplies treated water directly into the potable water supply distribution system. The water supply system servicing Greater Sydney is configured and operated to optimise yield, considering all sources of water.

The WaterNSW water supply system for Greater Sydney is an integrated network of dams, pipelines, canals, tunnels and rivers that has been designed, and is operated, to optimise overall water supply outcomes. It includes:

- the Warragamba system: comprising Warragamba Dam and the pipelines that connect the dam to the Prospect Water Filtration Plant and Prospect Reservoir
- the Shoalhaven system: comprising Tallowa Dam, Fitzroy Falls and Wingecarribee reservoirs, pipelines, canals and pumping stations which supplies local communities and Sydney via transfers either to the Warragamba system or the Upper Nepean system
- the Upper Nepean system: comprising Cataract, Cordeaux, Avon and Nepean dams, two diversion weirs and the Upper Canal that delivers water into Prospect Water Filtration Plant and/or Prospect Reservoir; this system supplies water to Sydney, the Illawarra, Macarthur and surrounding villages of Picton, Bargo and Thirlmere
- the Prospect system: comprising Prospect Reservoir and the Prospect Raw Water Pumping Station that delivers water into the Prospect Water Filtration Plant

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<sup>1</sup> <https://www.watnsw.com.au/documents/publications2/water-services/general-water-reports/Greater-Sydney-Water-Supply-System-Yield-Information-January-2025.pdf>

- the Woronora system: comprising Woronora Dam, and supplies Sutherland and adjacent villages
- the Blue Mountains system: comprising the Cascades, Greaves Creek and Medlow dams that supply the upper Blue Mountains. Water can also be transferred to the upper Blue Mountains from the Fish River Water Supply Scheme, which originates at Duckmaloi Weir. It should be noted that the Blue Mountains/Fish River Scheme dynamics are not modelled in detail in the Greater Sydney WATHNET Model – the subject of this review. The Blue Mountains/Fish River has its own WATHNET model, developed in detail, utilised to understand overall water security of this region.

All of the systems in the network contribute to WaterNSW's capacity to supply water. Any changes to the system infrastructure, or the operating rules that apply in any part of the system, affect the overall system yield.

## 1.2 This project

### 1.2.1 WaterNSW Operating Licence Requirements

Under Clause 36 of the WaterNSW Operating Licence 2024–2028, WaterNSW must engage an independent expert to review its model, modelling and processes for determining system yield. The review must:

- Ensure the modelling framework is robust and reflects good industry practice.
- Identify opportunities for improvement in model structure, assumptions, and yield estimation methodology.
- Consider stakeholder feedback, including from Sydney Water, IPART, and other relevant agencies.
- Be completed and reported to IPART by 30<sup>th</sup> June 2026.
- Include WaterNSW's response to the expert's findings, outlining which recommendations will be adopted and why.

### 1.2.2 Project purpose and scope

The purpose of this study is to undertake a thorough and critical review of the WATHNET Model, the input data, key assumptions and methodology used by WaterNSW in the determination of system yield, and the impacts of climate change, and ensure that the feedback of relevant stakeholders that have an interest in the determination of system yield is reasonably considered. The scope of work includes the following:

- Projection initiation and stakeholder feedback workshop
- Review of historical and stochastically generated hydrology data
- Review of the WATHNET water supply system model
- Review of the climate change impact on system yield analysis
- Independent expert panel review

The following topics were outside the scope for improvements for this project. WaterNSW will undertake the following as part of separate work packages in the future.

- Re-optimisation of the water values and drawdown rules for the reservoirs.

WaterNSW notes the 2021 review recommendation to consider the application of dynamic simulation for supply system analysis. WaterNSW will undertake the related analysis as part of a separate project, however relevant developments since the last review should be considered as part of the expert panel review and included in the review recommendations.

### 1.3 Approach taken

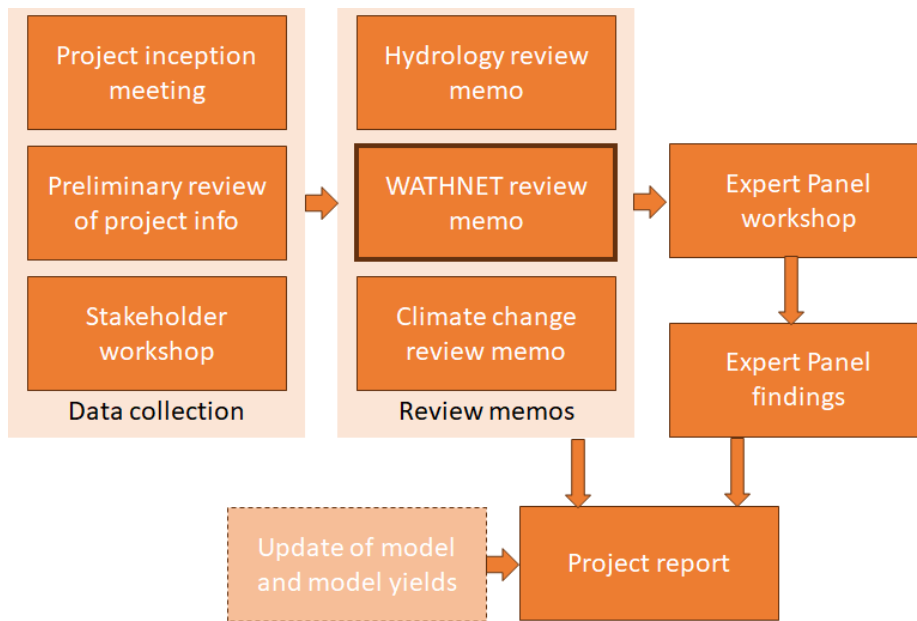


Figure 1-1: Overview of project tasks

In the first phase of the project, following collection of background information and stakeholder input, HARC prepared three separate review memorandums covering (a) hydrology, (b) the approach to climate change modelling, and (c) the WATHNET model and yield modelling approach for consideration by the Expert Panel. Following an Expert Panel Workshop and receipt of Expert Panel findings, this project report was produced taking into consideration this feedback as well as input from WaterNSW.

This project report documents the model review, stakeholder feedback, expert panel findings and includes recommendations for future enhancement.

Specific recommendations have been subjectively classified by HARC in the body of the report by their relative level of effort (low, medium, high) and prioritised (low, medium, high) based on their potential impact on model accuracy and/or estimates of yield. For the purposes of supporting WaterNSW’s implementation of the recommendations and engagement with IPART and other stakeholders in relation to this, the approximately 120 recommended actions described by HARC in the body of the report have been grouped into 33 categories. The review of the WATHNET model and yield calculation approach (Chapter 6) also grouped recommendations in that subject area as essential checks and corrections (to correct an error or omission, or to perform checks to confirm whether or not an error or omission has occurred), opportunities for improvement (to enhance model defensibility, model usability, or improve documentation) and industry/modelling practice (to retain a

current modelling practice, or to explore and potentially transition to a new modelling practice, as informed by contemporary good practice in the industry).

All recommendations are summarised and categorised in Section 8.

## 1.4 Review inputs

The review was based on the following inputs:

- Documentation and technical information provided by WaterNSW and collected from other sources
- Discussions at the Stakeholder Workshop and subsequent information provided by stakeholders
- Meetings with stakeholders and WaterNSW staff
- Feedback from WaterNSW on review reports
- Discussions at the Expert Panel Workshop and findings provided by Panel members

A list of the documents and technical data collected both at project inception and throughout the project is provided in Appendix A.

## 2. Stakeholder contribution to review

### 2.1 Stakeholder workshop

HARC facilitated a stakeholder workshop on the 24<sup>th</sup> February 2026 to provide an overview of the project approach, target technical areas for the review, and to gather stakeholder feedback on WaterNSW's model, modelling, and processes for determining the system yield. In addition to WaterNSW and HARC, the workshop was attended by representatives from NSW DCCEEW, Sydney Water, IPART, NSW Treasury, Wingecarribee Shire Council, Sydney Desalination Plant Ltd, Goulburn Mulwaree Council and Shoalhaven Water. The minutes of the workshop are in Appendix B.

Key discussion points raised by stakeholders were:

- The need to contextualise yield in the broader water security landscape (refer Section 6.2.4)
- Consideration of uncertainty around the single yield number (refer Section 6.2.3)
- Consideration of water quality triggers related to the ability to treat water (refer Section 6.1.5.5)
- Documentation of assumptions behind the demands provided by Sydney Water (refer Section 6.1.4.2)
- Consideration of local system representation and impacts e.g. Blue Mountains, supply to Kangaroo Valley and Nowra. WaterNSW confirmed that upper Blue Mountains demand was small relative to Greater Sydney demand and was excluded from the Greater Sydney model for computational efficiency, while lower Blue Mountains demand was represented within Orchard Hills demand and design criteria obligations. It was also noted that WaterNSW maintained a separate WATHNET model for the Blue Mountains/Fish River Water Supply Scheme
- Other (non-yield) applications of the WATHNET model e.g. drought management, transient-state modelling, policy testing, augmentation planning (refer Section 7).

Following the stakeholder workshop, HARC requested documentation outlining Sydney Water's climate change position and demand modelling assumptions under projected climate scenarios. Subsequent meetings were held with Sydney Water to discuss model inputs and with DCCEEW to capture and clarify the key points raised during the workshop. In addition, a follow-up meeting was conducted with NSW Treasury, involving both WaterNSW and HARC, to further understand and NSW Treasury's queries and feedback regarding the yield assessment process.

### 2.2 Stakeholder memos

Following the stakeholder workshop, Sydney Water and NSW Treasury provided additional written feedback. The original submissions are included in Appendix C- Stakeholder Written Feedback. Respective agency commentary is summarised below, with full submissions provided in the appendix.

#### **Sydney Water**

Key points of commentary:

- "Request for the yield review report to clearly articulate the broader purpose of the supply system model in assessing, monitoring and informing decisions to manage Greater Sydney's water security.

- “The report should also recognise the limitations of yield in understanding and defining water security risks and the role of other supply model outputs and measures.”
- The submission also stated that “yield should not be used alone for the purpose of planning and scheduling investment decisions. Other water supply model outputs combined with data from other sources can contribute for these purposes.”
- The submission requested that a “Clearer description of the model’s dependency on past inflow patterns and probabilities; and that its purpose is not to predict the timing, severity and/or duration of drought conditions.” That is, the yield modelling is not applicable to near-term forecasting and storage depletion from a current storage position.
- A plain English summary with commentary on key modelling input changes or trends since the last yield review was requested.
- Confirmation that yield modelling will capture Blue Mountains yield, Warragamba deep water pumping station (DWPS) operational understanding, full time flexible operation of Sydney Desalination Plant, and Water Sharing Plan rules.
- Yield should include consideration of rainfall independent supplies, contribution of different sources to yield, lower likelihood events, and that water availability can also be affected by raw water quality.

Much of the commentary provided regarded clarifying understanding of model applications and capabilities. These are further detailed in section 7.

Additionally, WaterNSW and the review process subsequently confirmed that full time flexible operation of Sydney Desalination Plant and Water Sharing Plan rules are incorporated into the model. Further work and review is required prior to incorporation of new DWPS operating assumptions.

## NSW Treasury

Key points of commentary:

- Emphasised discussed the need “to take decision makers on the journey”, and to better explain model application for different purposes.
- It asked that NSW Treasury Common Planning Assumptions be considered,
- Requested mapping of where WATHNET sits in the end-to-end decision process be considered.

Discussion of broader model use and context as raised at the workshop and in stakeholder meetings and memos has been included in Section 7 of this report to allow reflection on stakeholder concerns raised that were outside the scope of this project.

## 2.3 Stakeholder meetings

Detailed discussions with Sydney Water focused on the approach to demand derivation, including the treatment of water savings under restriction regimes and the supporting documentation. Sydney Water

also noted a requirement for model outputs corresponding to the highest climate change impact scenario (SSP2-4.5), consistent with its Climate Change Adaptation Position Statement.

The stakeholder meeting with DCCEE reviewed the modelling approach applied to the Greater Sydney Water Strategy (GSWS), including the methodology for yield assessment. This encompassed discussion of the number of stochastic replicates used, replicate thinning practices, and the associated error bounds. The application of water restrictions within the model was also examined, along with broader model uses and outputs such as probability curves.

Consultation with NSW Treasury discussed the written comments and queries provided. Key areas of focus included the need for improved transparency of modelling assumptions and methodologies, potential alignment of WATHNET outputs with input requirements for near- to medium-term augmentation decision-making, and clarification of the definition and interpretation of “long-term” within the context of yield analysis.

## 3. Expert Panel Review

### 3.1 Panel Makeup

Members of the expert panel were:

- KS Tan (Melbourne Water)
- Tim Purves (Icon Water)
- Brendan Berghout (Hunter Water)
- Emeritus Professor George Kuczera (University of Newcastle)
- Associate Professor Anthony Kiem (University of Newcastle)

Panel membership was selected by WaterNSW based on a long-list of suggestions from HARC and WaterNSW's list of previous independent reviewers. Panel membership was designed to include experts with specialist knowledge in different skill areas (hydrology, water resource modelling, climate change), and experience in different jurisdictions (within and external to Sydney and NSW).

### 3.2 Expert Panel workshop

The hydrology, climate change and WATHNET model review reports were provided to the Expert Panel in preparation for the Expert Panel workshop held on the 21<sup>st</sup> April 2026.

At this workshop the review process was briefly outlined and high priority recommendations from each of the review reports were discussed in detail. Panel members also provided some general feedback on the reviews.

Key items discussed include:

- **Hydrology**
  - Data quality and provenance
  - Climate data used
  - Pros and cons of gridded versus point data
  - Rainfall-runoff modelling approaches
  - Water balance on storage approach
  - Stochastic data generation
- **Climate change**
  - Approaches for representing climate change impacts
  - Climate change reference period and detrending
  - Covariate analysis
  - Use of paleoclimate data
- **WATHNET model and modelling**
  - Model calibration and validation
  - Operational constraints and water quality
  - Application of the Long-Term Average Annual Extraction Limit

- Demand zone and transfer system representation
- Stationary versus dynamic modelling
- The role of yield modelling
- Replicate thinning
- Modelling to inform augmentation decisions
- Design criteria and operating licence conditions

Detailed workshop minutes are included in Appendix E.

### 3.3 Expert Panel feedback

To ensure that all inputs from the Expert Panel were captured, following the workshop Expert Panel members were invited to provide their written findings. These are included in Appendix F.

Key findings of the Expert Panel included:

- **Hydrology**
  - Strongly endorse rigorous documentation and assessment of provenance of data for deriving the inflow records
  - Recommend generating paleo stochastic streamflow data using the same methods as NSW DCCEEW for generate paleo stochastic climate data to avoid the weakness of an approach that relies on rainfall-runoff models to convert climate variables into runoff
  - Recommend exploring alternative rainfall-runoff models and calibration and verification approaches more suitable for informing yield estimates
  - Support recommendations made for implementing stochastic data generation including assessment of stationarity in runoff record, explorations of seasonality and k-nearest neighbours, and a climate covariate
- **Climate change**
  - Expert panel supportive of investigating pattern scaling approach
  - Expert panel supportive of using temperature co-variate analysis to de-trend historical inflows with respect to global warming, to ensure that current yield is reasonably reflective of hydroclimate conditions under current level of global warming
  - Include temperature co-variate analysis as a data driven, second line of evidence for assessing future climate change impacts on yield
  - Add further discussion in the review on the effects of vegetation changes under higher carbon dioxide concentrations in the atmosphere
- **WATHNET model and yield modelling**
  - Review findings should not be constrained by the licence condition requiring reporting of yield
  - Greater consideration of dynamic modelling as an option including pros and cons
  - Consideration of replicate thinning
  - Suggestion of a test of the sensitivity of yield to the number of stochastic replicates being used and its convergence
  - Explicit representation of dead and active storage



- Consider greater reductions in demand at higher restriction levels
- Suggestion of another demand modelling approach where the demand model is embedded within WATHNET using input climate variables
- Review required of design criteria and operating licence conditions
- Consideration of drought contingency and drought management responses
- Consideration of optimisation of operating rules (referred to as water values in the WATHNET model)

Workshop discussions and written expert panel feedback were taken into consideration when producing this project report. As a result, some recommendations from the review reports were removed, others were modified and some added.

## 4. Review of historical & stochastically generated hydrology data

### 4.1 Introduction to the hydrology data review

This aspect of the review covers the data and modelling sources of the climate and hydrology inputs to the water resource modelling and advises on their suitability for determining the system yield to meet the requirements and obligations of the WaterNSW Operating Licence 2024-2028. In undertaking this review, HARC has considered industry guidance on hydrological methods for water resource modelling (Black *et al.*, 2011) and water resources planning (WSAA, 2024).

This review of historical and stochastically generated hydrology data includes the review scope (Section 4.2), the information that HARC received for the review (Section 4.3), HARC's review of WaterNSW's data documentation (Section 4.4) and the HARC review findings and recommendations (Section 4.5). The outcomes of any consultation by HARC with WaterNSW to clarify information during the review is captured in Section 4.4.

### 4.2 Scope of the hydrology data review

The scope of works for this aspect of the WaterNSW WATHNET Supply System model (herein referred to as the "WATHNET model") review was outlined in the WaterNSW Statement of Work (WaterNSW, 2026a) to:

1. "Review of the historical inflow, evaporation and rainfall datasets,
2. including proposed changes to methodology to develop historical input data for stochastic generation, and
3. advise on the suitability of the datasets for yield estimation."

Consistent with the other elements of the review of system yield, based on the WaterNSW operating licence requirements (IPART, 2024), the review assessed the robustness of the modelling framework to confirm that it reflects good industry practice, identified improvement opportunities in model structure, assumptions, and yield estimation methodology, and considered feedback from stakeholders and the expert panel members.

### 4.3 Information HARC received for the hydrology data review

HARC received the following information for this aspect of the review:

- WaterNSW (2026b) *WATHNET Model Review: Hydrology Updates*, which provided documentation on the sources of climate and streamflow data used to derive composite historical reservoir inflow timeseries;
- WaterNSW (2026c) *WaterNSW Rainfall-Runoff Model Development: Memo for 2026 WATHNET Model Review*, which documented the implementation of rainfall-runoff models relevant to WATHNET inflow inputs;
- Sample input datafiles to the WATHNET model for historical climate and inflows;
- Sample input datafiles to the WATHNET model for stochastic climate and inflows;

- Previous reviews of the WATHNET model inputs contained in Snowy Mountains Engineering Corporation (SMEC) and Sinclair Knight (1991), SKM (2011), WREMA and Kozarovski & Partners (2016), WREMA (2021) and Kuczera (2025).

Information was also sourced from an additional review by Sinclair Knight Merz (2003).

HARC also facilitated a stakeholder workshop as described previously in Section 2.1 as part of the information gathering for this review.

## 4.4 HARC understanding of WaterNSW approach

WaterNSW’s provided documentation on the sources of climate and reservoir inflow data used to derive composite dam inflow timeseries. Details of climate and hydrology data inputs and methods used for recent Calculated Monthly Catchment Runoff (CMCR) calculations were undertaken by WaterNSW for all the dams in the Warragamba, Metro, and Shoalhaven region dams, which are listed by dam region in Table 4-1 from approximately the 2000s. It is noted that WaterNSW structures including Blue Mountains Dams, Pheasants Nest Weir and Broughtons Pass Weir are omitted from Table 4-1 and this review as their hydrological inputs are not considered in the WATHNET model. The level of detail regarding climate and hydrology data and methods used for estimating inflows prior to the 2000s is variable and further discussed below.

Table 4-1. Dams by regions

Dam region	Warragamba	Metropolitan	Shoalhaven
Dam name	Warragamba	Avon Nepean Cordeaux Cataract Woronora	Fitzroy Falls Wingecarribee Tallowa

HARC’s understanding of the data inputs is summarised in the following section. Example plots use data from the WaterNSW file “CMCR\_1961to2004\_2025update\_Warragamba\_SILO\_evap.csv” provided for the review.

### 4.4.1 Historical data

#### 4.4.1.1 Rainfall

Rainfall data were used as inputs to:

- Regression relationships and water balance models used to estimate reservoir inflows prior to 1960 (further described in Section 4.4.1.3.1);
- Legacy CMCR calculations from approximately 1960 -1998 (further described in Section 4.4.1.3.2); and
- The Hydrological Simulation Program – FORTRAN (HSPF) rainfall-runoff model (further described in Section 4.4.1.3.3).

Based on the documentation provided, there have been changes in the data sources used for rainfall time series over time, with rainfall data collected at point rainfall gauges used for derivation of some inflows and gridded rainfall data (from SILO) used for others.

Gridded SILO rainfall data were used in the following applications:

- The 2025 WATHNET model update for 1909-2024 simulations;
- Calculation of net evaporation over entire historical period; and
- Parameterisation of stochastic data generation.

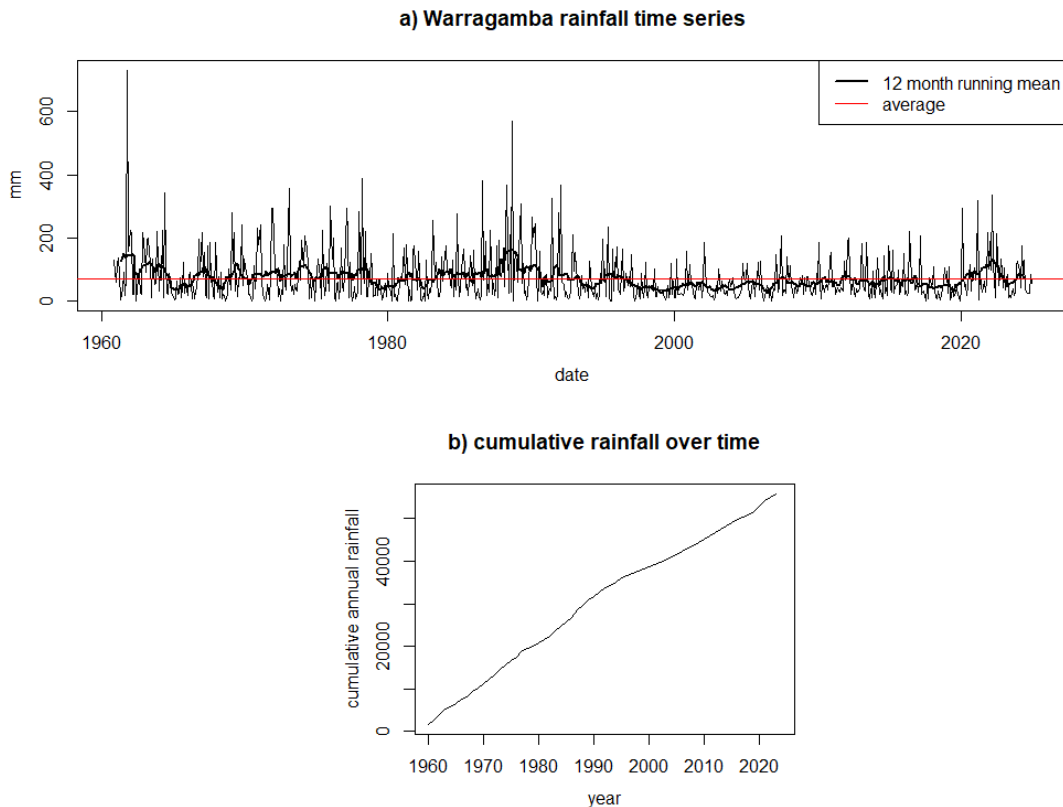


Figure 2. Rainfall used to calculate current CMCR for Warragamba showing a) time series of monthly (black), 12 -month rolling average (thick black line), and average (red) rainfall and b) cumulative annual rainfall over time.

#### 4.4.1.2 Historical consideration of evaporation

Gridded SILO evaporation data were used in the same applications as the gridded SILO rainfall data listed above in Section 4.4.1.1.

The SKM (2011) review developed monthly factors for transposing monthly pan evaporation from Prospect Reservoir to equivalent Penman Monteith evaporation estimates for Lake Burragarang. These factors are used in CMCR estimates (WaterNSW, 2026b).

The 2025 WATHNET model update utilised evaporation data sourced from the SILO database. Previously, lake evaporation at Warragamba (consisting of a composite time series of pan evaporation from Prospect Reservoir station converted to an equivalent Penman-Monteith value with monthly average values adopted post 2019) was applied to all nine storages listed in Table 4-1. In contrast, the evaporation data is now derived from SILO estimates of shallow lake evaporation with two monthly factors applied to achieve:

1. A conversion from SILO shallow lake evaporation data to an equivalent pan evaporation value (a multiplicative factor that is  $> 1$  for all months and locations, referred to as factor **F2**); and

2. A conversion from an equivalent pan evaporation value to a Penman-Monteith estimate (a multiplicative factor that is  $< 1$  for all months and locations, referred to as factor **F1**).

The use of these two multiplicative factors results in the SILO shallow lake evaporation data being **scaled up** for:

- June, July, and August at Warragamba;
- June, July, August and September at the Metro dams; and
- June at the Shoalhaven dams;

And **scaled down** for all remaining months.

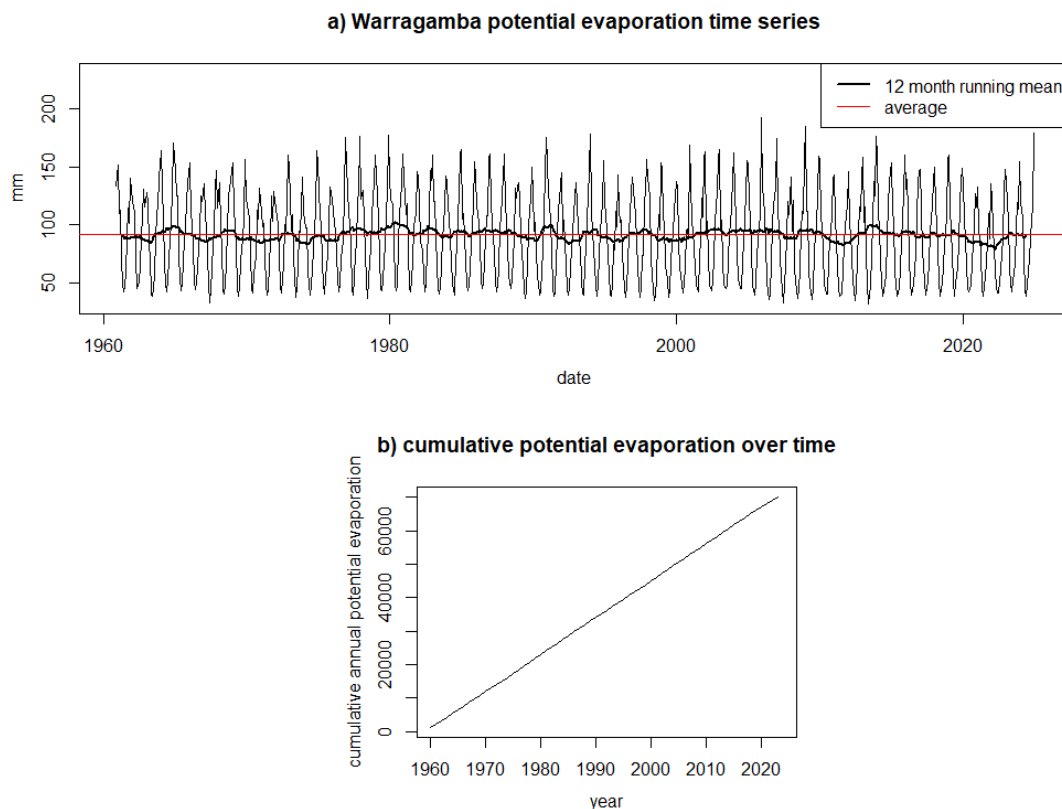


Figure 3. Potential evaporation used to calculate current CMCR for Warragamba showing a) time series of monthly (black), 12 -month rolling average (thick black line), and average (red) evaporation and b) cumulative annual evaporation over time.

#### 4.4.1.3 Historical derivation of streamflow

The dam inflows may be gauged or modelled values representing either pre- or post-dam streamflows. WaterNSW has applied methods for converting post-dam streamflows to equivalent pre-dam flows using the CMCR method (Section 4.4.1.3.2).

Inflows to the 12 dams are comprised of data composited from the following six sources:

- Gauged pre-dam streamflow
- Transposed streamflow
- Regression relationships between pre-dam streamflow and rainfall at the relevant sites
- A water balance calculation using the Calculated Monthly Catchment Runoff (CMCR) method for the post-dam period

- HSPF rainfall-runoff models
- Water balance models calculated at Warragamba Weir prior to dam construction. The composited data, also known as “Composite WATHNET”, span the period 1909–2024. An example of the inflow time series is shown for Warragamba in Figure 4. It is recognised by WaterNSW that the documentation for some of the methods used for deriving historical flows is insufficient to inform a comprehensive or definitive assessment of errors or uncertainties. Additionally, the SKM (2011) report noted that derived inflows into Warragamba and the Upper Nepean dam prior to 1960 are considered representative of pre-dam runoff.

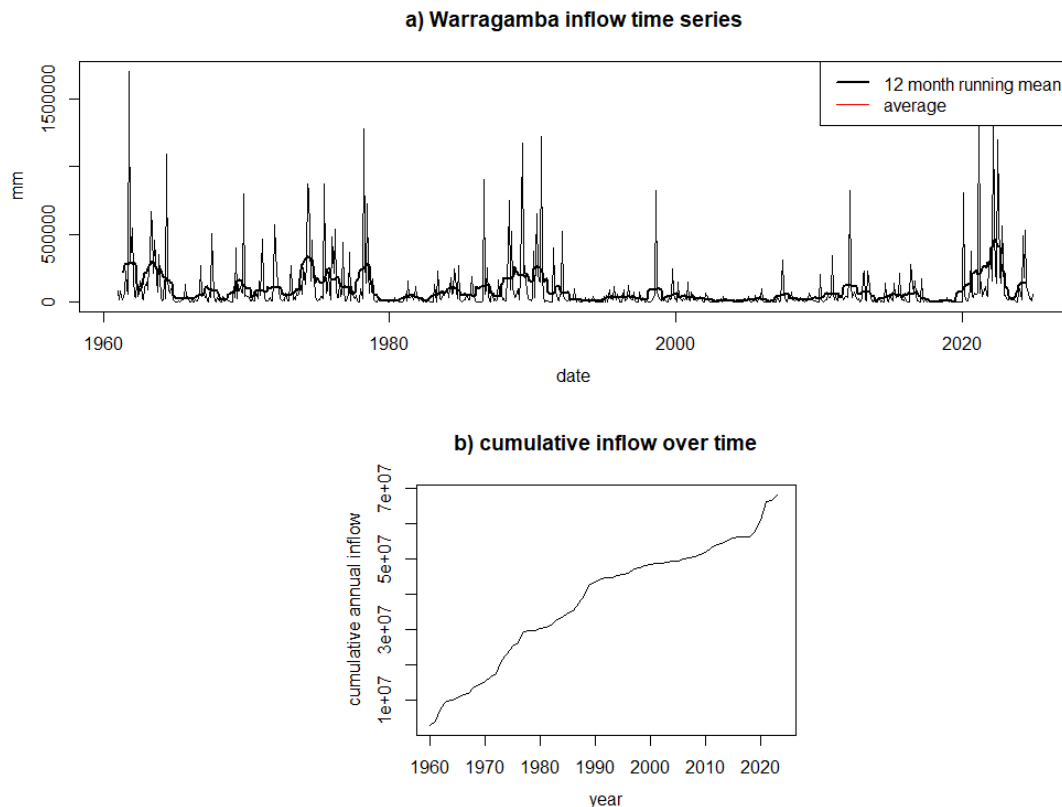


Figure 4. Potential evaporation used to calculate current CMCR for Warragamba showing a) time series of monthly (black), 12-month rolling average (thick black line), and average (red) inflow and b) cumulative annual inflow over time.

#### 4.4.1.3.1 Regression relationships

Monthly non-linear regression relationships have been used to calculate inflows as a function of monthly rainfalls for the purpose of extending inflow data. These regression models were documented in the Snowy Mountains Engineering Corporation and Sinclair Knight (1991) review and are also shown in Table 6-3 of Sinclair Knight Merz (2003). The regression equations are specific to each dam with both point and weighted catchment-averaged rainfalls used as covariates.

#### 4.4.1.3.2 Calculated Monthly Catchment Runoff (CMCR)

Streamflow estimated using CMCR is used from around 2007 onwards for all dams. In addition, CMCR values calculated using legacy methods are used from 1960 through to the late 2000s for five of the 12 dams – Warragamba, Cataract, Cordeaux, Nepean, and Avon. The CMCR method accounts

for reservoir releases, post-dam catchment runoff and direct rainfall on the reservoir by considering the corresponding changes in the reservoir surface area.

The implementation of CMCR has evolved over time. CMCR estimates for inflows from 1999 onwards were recalculated by WaterNSW to be consistent with the internal water balance calculations that are undertaken within WATHNET. The current CMCR inflow calculations therefore reflect pre-dam runoff conditions, as the impact of the reservoir inundation area on both catchment runoff and rain on reservoir effects is modelled dynamically in WATHNET.

Once a reservoir is constructed, the inflows calculated from a reservoir water balance will not represent inflows under pre-dam conditions, due to rainfall and evaporation on the surface of the reservoir and altered inflows from the exposed lake bed. A previous review recommended that pre-dam inflow calculations should explicitly allow for the rainfall and evaporation fluxes from the reservoir (Kuczera, 2025). The most recent methodology used in the CMCR calculation is to calculate the inflows to the dam using a storage mass balance that explicitly accounts for rainfall on, and evaporation from, the lake.

This water balance method proposed by WaterNSW was endorsed in Recommendation 12 of the Kuczera (2025) review. In addition, an approximation of the runoff from the exposed lakebed is made using empirical equations to first calculate the rainfall excess and then convert it to a runoff from the exposed lake bed, conditional upon the antecedent rainfall. The consideration of runoff from the exposed lake bed is used in more recent versions of the CMCR and is an update from previous CMCR methodology that adopted an assumption that the exposed lake bed was 100% impervious.

It is noted in the WaterNSW data preparation file “CMCRInflow\_Dec2024\_Legacy.xlsx” that legacy CMCR calculations are used for dates prior to and including:

- December 2007 for Cataract, Cordeaux, Avon, Nepean, Woronora, Warragamba, Fitzroy Falls, and Tallowa Dams
- May 2009 for Wingecarribee Dam

In this spreadsheet, the legacy CMCR calculations are available from January 2007 onwards.

CMCR calculations used for the 2025 WATHNET model update using lake evaporation data derived from SILO evaporation data are available from:

- January 1961 to December 2025 for Warragamba (anomalous inflow for August 1998), Woronora, Avon, Cordeaux and Cataract (both with gaps at December 1998)
- January 2013: Tallowa, Fitzroy Falls
- January 1999: Wingecarribee
- December 1998: Nepean

#### **4.4.1.3.3 Hydrological Simulation Program – FORTRAN (HSPF)**

The HSPF rainfall runoff model was used to model unimpounded catchment conditions. The climate data inputs used were point rainfall and pan evaporation data. The primary objective in the calibration of the HSPF model was to reproduce monthly flow duration curves to inform climate change analysis of while a secondary objective was to reproduce lower range flows at a daily scale to support environmental flow releases (SKM, 2011). The reproduction of monthly flow duration curves was targeted to support analysis of climate change, however the specific climate change impact being

assessed (e.g. environmental flows, water sharing plans, yield assessments) is unknown. The HSPF model is a legacy model that is being phased out and progressively replaced since around 2015 with Sacramento rainfall-runoff models (developed within the eWater Source modelling platform). The Sacramento rainfall-runoff models are similarly developed for the purpose of informing environmental flow releases.

#### 4.4.1.3.4 Sacramento Rainfall-Runoff Model

The Sacramento models have been developed to inform operations and water sharing plan related activities by modelling daily flow characteristics (A. Lal, WaterNSW, pers. comm. To HARC 10<sup>th</sup> April 2026). AWAP gridded rainfall and AWAP gridded evaporation are used as inputs (WaterNSW, 2026c).

#### 4.4.1.3.5 WATHNET nodal inputs

The updated 2025 WATHNET model uses the following nodal input files (A. Lal, WaterNSW, pers. comm. To HARC 4<sup>th</sup> April 2026):

Table 4-2. Input data sets used for historical and stochastic runs of the 2025 WATHNET model

Historical run	Hist_Nodal_1909-2024_NetEvap.txt
Stochastic run	10k_100yr_1909-2024_EvapRain_netevap

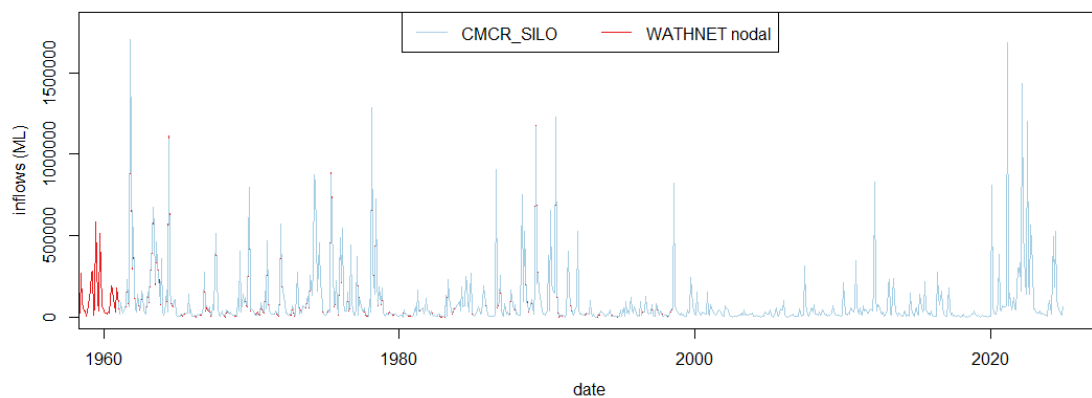


Figure 5. Time series of WATHNET nodal input from Hist\_Nodal\_1909-2024\_NetEvap.txt and CMCR inputs calculated using SILO evaporation for Warragamba.

### 4.4.2 Stochastic data

#### 4.4.2.1 Stochastic data generation

The stochastic generation in WATHNET is structured as a two-stage multi-site probability model as follows:

1. Seasonal variates are randomly sampled using the parametric model MSSSCAR (Multi-Site, multi-Season, multi-State Contemporaneous AutoRegressive model) (Kuczera, 2020); and
2. The generated seasonal values are then disaggregated to monthly values using a non-parametric model based on the k nearest neighbour (kNN) algorithm and the method of fragments.

In the following sections, files received from WaterNSW are referred to by both their file name, and the data directory in which they were located, in the transfer of background information from WaterNSW to HARC for this review. This is simply to enable WaterNSW to trace any individual files that HARC is referring to.

From “\15. Stochastic Gen Outputs\parameters.txt” and “\15. Stochastic Gen Outputs\diagnostics.txt”, the following selections for the Greater Sydney WATHNET model are evident:

- Use of a single season per year, with water years represented by calendar years (January to December);
- Use of 19 sites consisting of 9 inflows, 3 lake evaporations, 3 lake rainfalls, 4 demand factors;
- Box-Cox data transformation optimised to minimise the skew; and
- Lags of up to 4 seasons (i.e. years – see first dot point) were considered with lag of 1 adopted.

The full period of historical data was used to calibrate the MSSSCAR model using  $k = 1$  nearest neighbours (A. Lal, WaterNSW, pers. comm. To HARC 24<sup>th</sup> March 2026). The data were generated using the observed median for  $t = 0$ . Replicates of 10,000 years of monthly data were generated 100 times.

#### 4.4.2.2 Application of stochastic data

Stochastic data was generated by adopting the historical median values for data at  $t = 0$ . This fixed antecedent condition in the stochastic data generator impacted the evaluation of yields in the first few years of every simulation. To address this memory in the generation of stochastic data, 100 replicates containing 10,000 years of monthly stochastic data (a total of  $10^6$  years of data) were generated using MSSSCAR. Each replicate was post-processed to separate these  $10^6$  years of simulations into 20,000 replicates each containing 50 years of data.

Net evaporation is not directly generated in WATHNET as the stochastic generator is constrained by the Box-Cox transformation to generate positive values. The stochastic data for rainfall and evaporation are instead post-processed in R to calculate net evaporation.

The WATHNET model was then run to estimate yield over 50-year time periods 20,000 times.

The two data sets considered in the first instance were identified as the sample inputs used in the 2025 WATHNET model (shown in Table 4-2):

- “\14. Stoch Nodal\Stoch 1909-2019\_evap update\10k\_100yr\_1909-2019\_EvapRain\_2\_netevap”:  
this file contains 20,000 replicates of monthly data dated 2020-2069 (50 years); and
- “\14. Stoch Nodal\Stoch 1909-2024\10k\_100yr\_1909-2024\_EvapRain\_netevap”:  
this file contains 20,000 replicates of monthly data dated 2025-2074 (50 years)

Both data files contain 9 dam inflows, net evaporation for the three dam regions, demand factors for 4 regions, and lake evaporation for the metro dam region. It is noted in both files that the generated replicate length was adjusted in R, as was a post-processed calculation of net evaporation.

In addition, the following file appears to contain the original stochastically generated data:

- “\14. Stoch Nodal\Stoch 1909-2024\10k\_100yr\_1909-2024\_EvapRain”

This file contains 100 replicates dated 2025-12024 (10,000 years) of dam inflows, demand factors, lake evaporation, and lake rainfall. This data file contains the note that data was generated using calibration data from the following file:

- “\10. Hist Nodal Data Files\Hist\_Nodal\_1909-2024\_EvapRain.txt”  
This file contains data from 1909-2024 (116 years).

No replicate thinning was undertaken, as all stochastic replicates generated were used to produce yield estimates that are consistent with the criteria for yield specified in the operating license.

## 4.5 Review findings and recommendations for hydrology data and models

Based on the information provided for the review, our understanding of WaterNSW’s current practices, and our knowledge of methods used to derive suitable climate and hydrology inputs for assessing system yield by other urban water service providers, researchers, and government agencies, HARC offers review findings and recommendations organised by general documentation, rainfall, evaporation, streamflow, and stochastic data. A summary of recommendations is made within each subsection and are compiled in Section 8.

The recommendations may have some impact on yield estimates. In addition, they will improve the clarity and defensibility of WaterNSW’s hydrologic methods. The impact on yield estimates resulting from some recommendations will not be precisely known until those recommendations have been implemented. The review of data inputs will be determined by the results of the data assessments recommended below, recognising that the examination and clean-up of data can be the most time-consuming step in modelling water resources. The challenge of establishing the provenance of data sources and methods of legacy approaches is recognised but documentation of legacy approaches that are currently in use is critical to establish whether their continued use in contemporary applications remains appropriate.

### 4.5.1 General documentation

Clear documentation is required to ensure transparency, allow work to be reviewed and reproduced, and provide a record of the evidence and reasoning that underpin decisions. Clear documentation will also aid in the recognition of where and when revisions are necessary. In developing documentation, it should be readily discoverable, and the contents should be accessible to future readers in consolidated, well-structured reporting. It should provide necessary context, stating and clarifying assumptions, with quality control or quality assurance checks on the data and methods as applied. Improved documentation will improve transparency in the modelling process, which should increase both WaterNSW and stakeholder confidence in the model results.

### 4.5.2 Historical data

The risk of bias in the use of gridded climate records, such as AWAP or SILO rainfall and evaporation data products, was outlined in Section 6.2 of Kuczera (2025) and has been shown to exhibit significant differences with gauged rainfall records with respect to annual rainfall totals (Tozer *et al.*, 2012). Biases in gridded climate data may arise from changes in the network of observation sites used to measure the data over time and how gridded surfaces are interpolated from those changing networks of sites. Uncertainties and biases in gridded climate inputs are often amplified in the conversion to

runoff, which is driven by the differences between rainfall and actual evaporation over time. This is especially the case for SILO evaporation data that has used both interpolated pan evaporation data and evaporation estimates calculated from other climate variables (solar radiation, temperature, wind speed and humidity).

The presence of biases in the gridded data should be examined against high quality gauged data available from the Bureau of Meteorology (2026), which have been controlled to ensure consistent and reliable observations. The examination of both rainfall and evaporation would be to ensure against the introduction of spurious trends and step changes resulting from the compositing of data from multiple sources. This can be checked by examining double mass curves. Spurious trends should be examined to identify a source of a non-climatic trend (e.g. changes in instrumentation or location within the site) to ensure against the removal of real climate trends that may appear as a result of differences between the target and reference gauge locations and surrounding topography.

As stressed in the review by Kuczera (2025), the “integrity of the historical data underpins the integrity of yield estimates”. Approaches for examining historical rainfall and evaporation data sets, particularly if rainfall-runoff models are used to derive reservoir inflows, are further detailed in the subsections below.

#### 4.5.2.1 Rainfall

At present, gauged rainfall is used to derive inflows using the CMCR method for the period post 1997 and likely used in earlier CMCR estimates. The use of gridded data is appealing as it contains no missing data and bypasses the need to infill gauged data sets that often contain some periods of missing records. If gridded rainfall needs to be used it should be validated, as discussed in Section 4.5.2 above, against high quality gauged data to identify non-climatic trends.

Differences in gridded rainfall compared to gauged rainfall are compounded when used to model streamflow – the effects are exacerbated if gridded data is also used to calibrate the model (Tozer et al. 2012). The network of rainfall gauges used to model gridded data becomes increasingly sparse further back in time and the use of gridded data to model runoff prior to the mid twentieth century risks the introduction of inconsistencies in the record. We therefore strongly recommend using gauged rainfall when rainfall-runoff models are used to extend the inflow record back in time to ensure consistency in the data inputs and minimise errors introduced by inconsistencies in deriving gridded rainfall estimates from site networks that change over time.

If gauged records are unavailable and gridded rainfall data can be validated, its use in rainfall-runoff models can be justified if it is able to produce equivalent or improved calibration metrics compared with gauged rainfall.

For each location, a consistent data set should be adopted for deriving all the inflows, whether this is using rainfall inputs from a single gauged site, multiple gauges, or gridded data. Checks for non-climatic trends, as discussed in Section 4.5.2 above, should be performed on the adopted rainfall series and the subsequent modelled runoff, paying particular attention to periods when data sources change.

Observational data inputs and calculation methods used to derive SILO gridded products evolve and it is therefore essential that documentation or suitable metadata is maintained regarding when that data was accessed.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H1: Develop or maintain documentation or metadata of when climate datasets were obtained from SILO and incorporated into modelling workflow.	Low	Low
#H2: Develop or maintain documentation regarding the timing (at the same temporal resolution as the data sources) of transitions between data sources for rainfall and justification for changing data sources.	Low	None
#H3: Use gauged rainfall for deriving streamflow where possible unless gridded rainfall is the only available source of data and its use can be validated.	Medium	Low
#H4: Identification of non-climatic trends or step changes: for each rainfall time series used in either WATHNET, CMCR calculations or rainfall-runoff modelling, a consistent set of exploratory plots be produced for the period 1909-2025 including: <ul style="list-style-type: none"> <li>Monthly time series plots</li> <li>Cumulative totals versus time</li> <li>Cumulative total against cumulative totals at the nearest Bureau of Meteorology climate change reference site (see <a href="https://www.bom.gov.au/climate/change/hqsites/">https://www.bom.gov.au/climate/change/hqsites/</a>).</li> </ul>	Medium	Medium

#### 4.5.2.2 Evaporation

Non-stationarities in the Prospect Reservoir pan evaporation time series have been noted in previous reviews. These shifts arose from changes in measurement techniques that cannot be corrected for, including discontinuation of the primary measurement site. The use of a consistent evaporation data set has implications for the derivation of inflows. This was previously demonstrated in Sinclair Knight Merz (2003) where non-stationarities in the inflows at Warragamba, Metropolitan dams, Shoalhaven dams and the Upper Shoalhaven River (and Penrith Weir) were examined, with many streamflows displaying inhomogeneities, where the timing of many of the shifts aligned with changes in the evaporation record used in water balance calculations. Recommendations were made in the SKM (2011) review that reservoir evaporation estimates using pan evaporation data be replaced with estimates using climate data. The review by WREMA and Kozarovski & Partners (2016) stated that reservoir evaporation estimates were in the process of being revised. WaterNSW has adopted lake evaporation time series that are derived from SILO shallow lake evaporation for the duration of 1909-2024, consistent with the recommendation in the SKM (2011) review.

Given the existence of both current and legacy CMCR estimates, clarity should be provided in the documentation as to whether the conversion factors for transposing monthly pan evaporation from Prospect Reservoir to equivalent Penman Monteith evaporation estimates for Lake Burragarang were applied to the legacy CMCR estimates and if the SILO evaporation time series has been used to recalculate the inflows.

Ensuring that the input evaporation data is representative of historical climate is paramount for the adequate estimation of water yields. This can be achieved by comparing trends in the SILO evaporation data with Bureau of Meteorology climate change reference sites. For example, a double mass curve check between the derived evaporation shown in Figure 5 and evaporation from a reference site would provide a check for step changes or non-climatic trends. Such comparisons should be undertaken before any derivation of inflows and water yield modelling is undertaken with any updated climate data.

The evaporation adjustment factors need to be clearly documented, an example of which is shown in Table 4-3.

Table 4-3. Monthly dam-region-specific factors used to adjust evaporation

Pan to Penman-Monteith Factors	Warragamba		Metro		Shoalhaven	
	F1	F2	F1	F2	F1	F2
January	0.78	1.08	0.8	1.07	0.8	1.06
February	0.77	1.07	0.87	1.06	0.87	1.05
March	0.81	1.07	0.88	1.07	0.88	1.06
April	0.82	1.08	0.78	1.09	0.78	1.06
May	0.82	1.17	0.82	1.21	0.82	1.16
June	0.9	1.29	0.81	1.35	0.81	1.26
July	0.9	1.26	0.8	1.31	0.80	1.21
August	0.89	1.16	0.84	1.22	0.84	1.16
September	0.83	1.10	0.9	1.15	0.90	1.09
October	0.78	1.06	0.88	1.08	0.88	1.03
November	0.76	1.05	0.85	1.06	0.85	1.02
December	0.79	1.07	0.8	1.07	0.80	1.04

Similarly, a table similar to Table 4-4 would be valuable in WaterNSW’s documentation to summarise how evaporation estimates have changed as a result of adopting new data sources.

Table 4-4. Summary of mean annual evaporation for all regions resulting from different data sources and calculation methods

	Dam region	Warragamba	Metro	Shoalhaven
Annual average evaporation estimate (mm/yr)	SILO Morton shallow lake	1255	1219	1171
	Previous WATHNET value	930		
	Derived value using in 2025 model update	1100	1131	1326

Of greater importance is that the two conversion factors applied to the SILO  $M_{lake}$  data appear to be part of a methodology derived from the previous use of pan evaporation data from Prospect Reservoir and the need to consider the impact of energy storage and advection in deeper lakes on evaporation. It appears that the methodology now serves to:

1. convert SILO  $M_{lake}$  data to an equivalent pan evaporation data assumed to be sourced from SILO pan evaporation data; and
2. adjust the pan evaporation data to account for lake energy dynamics.

The first conversion factor (F1) is described as allowing a conversion from pan evaporation to a “Penman-Monteith-based lake evaporation estimate”. The methodology and data used to define the F1 conversion factors should be clarified.

The term “Penman-Monteith-based lake evaporation estimate” is ambiguous as Penman-Monteith (1965) is a measure of potential evapotranspiration and is typically used in agricultural applications as it concerns evapotranspiration. The original Penman-Monteith equation is not deemed suitable for estimating lake evaporation (McMahon *et al.*, 2013), however, it is possible that the “Penman-Monteith-based lake evaporation estimate” is referring to a measure based on Penman-Monteith that

incorporates an equilibrium temperature (McJannet *et al.*, 2008), Penman plus Kohler and Parmele (Kohler and Parmele, 1967), or Penman plus Vardavas-Fountoulakis (Vardavas and Fountoulakis, 1996). If this is the case, then the method of estimating evaporation may be acceptable (McMahon *et al.*, 2013) but terminology needs to be updated to avoid ambiguity. However, the preferred method for estimating lake evaporation is to use Morton evaporation (McMahon *et al.*, 2013). Directly using  $M_{lake}$  variable from the SILO data set would therefore be an acceptable option for reservoirs where the maximum depth is less than 30 m, provided the data meets relevant quality checks.

It was previously recommended in SKM (2011) that deep lake effects be considered as energy storage in a deep lake affects the amount and timing of evaporation. In HARC’s experience, the differences in estimates of evaporation using Morton equations relevant to shallow lakes and deep lakes are substantial. There exist numerous ways to consider deep lake effects (e.g. Kohler and Parmele, 1967; Vardavas and Fountoulakis, 1996). HARC recommends the adoption of Morton’s Deep Lake Evaporation based on the recommendation in McMahon *et al.* (2013). The Morton-based method applicable for estimating evaporation from a deep lake can be calculated using the program WREVAP. WREVAP was originally a Fortran program that has since been developed into Python<sup>2</sup>. The calculation uses inputs of temperature, humidity, and solar radiation, which are available from SILO data sets.

WaterNSW should also maintain interest and awareness in how reservoir evaporation is estimated by other major reservoir owners around Australia. For example, Melbourne Water are currently testing the use of the Complementary Relationships Method, a method developed following recommendations from a CSIRO study published in 2000 that derives reservoir evaporation from operational storage data.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H5: Develop or maintain documentation or suitable metadata of when gridded climate datasets were obtained from SILO and incorporated into modelling workflow.	Low	Low
#H6: Develop or maintain documentation regarding the timing (at the same temporal resolution as the data sources) of transitions between data sources for evaporation, justification for changing data sources, and use unambiguous variable names.	Low	None
#H7: Investigate and if appropriate adopt estimates of lake evaporation using Morton-based methods for deep lake evaporation for reservoirs deeper than 30 m.	Low	Low
#H8: Identification of trends or step changes: for each evaporation time series used in either WATHNET, CMCR calculations or rainfall-runoff modelling, a consistent set of exploratory plots be produced for the period 1909-2025 including: Monthly time series plots Cumulative totals versus time Cumulative total against cumulative totals at the nearest Bureau of Meteorology climate change reference site (see <a href="https://www.bom.gov.au/climate/change/hqsites/">https://www.bom.gov.au/climate/change/hqsites/</a> ).	Medium	Medium

<sup>2</sup> <https://github.com/WSWUP/WREVAP/tree/Python3>

### 4.5.2.3 Streamflow

It is essential that the provenance of the data inputs to WATHNET and the methods used to derive them are clearly documented.. The methods, or hierarchy of methods used, should be consistently applied over the full time series unless there are well-documented and robust reasons for adopting different approaches for particular periods for some inputs. The current reporting does not yet provide sufficient clarity on the detailed source data, the precise transitions between derivation methods, or the extent to which different methods have been combined within individual inflow records. For example, sources of data for each of the inflows are provided as colour-coded blocks of five years, although for several of the inputs (see SKM, 2011) it is known that this is a simplification, with transitions between methods within those five-year blocks. This lack of transparency is most evident for the earlier parts of the record (typically pre-1960), where published reports describe the broad derivation methods but do not always provide enough detail to fully reconstruct the underlying calculations for each period of the input series.

Recommendations were made in the SKM (2011) review that inflow estimates for Avon, Nepean, and Cordeaux Dam be made using a rainfall-runoff model to replace estimates made using regression models that dampened inflow variance. The expert panel for the SKM (2011) review stated that the regression relationships should not be used for estimating historical inflows.

It was also recommended that dam inflow estimates be extended back in time to 1850 (WREMA and Kozarovski & Partners, 2016), which would allow consideration of earlier rainfall data including the Federation Drought. The review by WREMA and Kozarovski & Partners (2016) stated that inflow estimates extending back to 1850 were in the process of being developed, but this was then not referred to again in more recent reviews or memos. Both the SKM (2011) and WREMA and Kozarovski & Partners (2016) reviews recommend the recalibration of rainfall-runoff models to ensure they are valid for informing yield estimations (further detailed in Section 4.5.2.3.2). The rainfall-runoff model recalibration is labelled as a high priority in the SKM (2011) review. In addition, the extension of the dam inflow methods back in time to 1850 is dependent on the suitability of climate inputs over this period, which would need to be demonstrated in line with the recommendations made in Sections 4.5.2.1 and 4.5.2.2 prior to their use in inflow derivation.

It is recognised in the Hydrology Memo that, “As different periods within the reconstructed record are estimated using different approaches, the composite record is not homogenous...”. The estimation methods are identified as a potential source of discrepancies. It is also noted elsewhere in the Hydrology Memo that land use and land cover has changed significantly in some catchments, and this change should be explicitly identified as another potential source of trend in the rainfall-runoff response. Furthermore, changes in the data sources used to estimate inflows may introduce step changes (as previously discussed in Sections 4.5.2.1 and 4.5.2.2). Any signals introduced by either changes in estimation methods, significant catchment characteristics, or data sources, should be clearly documented. These changes will flow through the stochastic data generation (further discussed in Section 4.5.3), which could influence yield estimates.

It is recommended that WaterNSW develop and adopt a hierarchy of methods for deriving inflows and have these derived inflows consistent with respect to approximating un-impounded runoff conditions. For example, composited inflows should first be derived using pre-dam gauged data. Inflows following the construction of the dam can then be estimated using a water balance approach, namely CMCR using the most up to date methodology. The inflow time series could then be supplemented with streamflow modelled using Sacramento, replacing existing estimates made using regression and

unknown models and data sources. The composited flows should then be quality checked to ensure that changes in methods and data source do not introduce spurious inhomogeneities.

Previous reviews have permitted the use of the composited inflows, currently in use for the historic period prior to approximately 2007. However, these reviews were accompanied by strong recommendations on the provisional use of these composited inflows with respect to:

- The assessment of inhomogeneities in both data sources and calculated inflows;
- Recalibration of rainfall-runoff models to ensure results are suitable for yield estimation; and
- Ensuring consistency in the method used to calculate the inflow time series.

It is recommended that these aspects are addressed for the inflows derived using legacy methods prior to approximately 2007.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H9: Develop or maintain documentation regarding the timing (at the same temporal resolution as the data sources) of transitions between data sources, justification for changing data sources for estimating inflows, and transitions between inflow estimation methods for all relevant dams including transposed data sources. The current visual summary shown at a resolution of 5 years is too coarse to be interpreted without ambiguity. Details of these inflows appear in Sinclair Knight Merz (2003) but contemporary records should be kept in line with best practice guidance.	Low	None
#H10: Ensure that the distinction between pre-dam and post-dam runoff is stated clearly and consistently. Clear labelling of inflow types would improve interpretability for readers who are not closely familiar with the historical evolution of the modelling approach.	Low	Unknown – dependent on whether assumptions are consistent with model configuration
#H11: Develop and maintain documentation on the rationale for retaining legacy streamflow input datasets for the 1909 to approximately mid-late 2000s period, and the periods of inflow data subject to review or update. In particular, include a clearer explanation in the documentation of why inflows for the 1960–2007 period from previous model updates have been preserved, when it appears that the revised CMCR analysis could be used to regenerate the monthly inflows for this period.	Low	Medium*
#H12: Provide an explanation of why recommendations made in previous reviews to recalibrate rainfall-runoff models have yet to be adopted. A high-priority recommendation was also given to using rainfall-runoff model results for all sites in place of the regression relationships that likely underestimate the true variability of flows.	Low	None
#H13: Replace water balance values and regression-based values prior to the 1960s with CMCR estimates. If CMCR estimates cannot be applied for these locations and time periods, replace with results from rainfall-runoff models that are suitable for yield estimation.	Low	Medium

\*Likely impacts on yield estimation may be low but impact on stochastic generation and climate change impact assessment are likely to medium to high.

#### 4.5.2.3.1 Calculated Monthly Catchment Runoff (CMCR)

Justification should be provided for the adjustments made to the CMCR inflows for effective rainfall on the exposed lake bed, namely for the calculation of  $P_{\text{effective}}$  (refer WaterNSW Hydrology Memo). The theoretical justification and empirical data used to validate these adjustments should be referenced in

model documentation. In addition, the time periods over which these adjustments were applied should be clearly documented.

It is also recommended that the impact of runoff from the lakebed calculated in CMCR be quantified so that its relative influence on the system yield can be understood. Similarly, an assessment of the temporal changes in reservoir surface area relative to the catchment area could be made. If changes in the surface area of the reservoir are found to be small, it would be pragmatic to ignore runoff from the exposed lakebed.

It was noted that negative inflows are not redistributed using the current approach. Methods for dealing with this are discussed in Section 4.5.2.3.3.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H14: Maintain documentation of how empirical equations for runoff from lakebed were derived and assess the relative impact of this runoff on overall inflows and system yield.	Low	None

#### 4.5.2.3.2 Sacramento model

Sacramento rainfall-runoff models of inflow catchments to the WATHNET model have been progressively developed, to inform environmental flows, since around 2015. We understand that these models have been calibrated using the default objective functions and note that not all modelling packages offer suitable objective functions for the purpose of estimating runoff for the purpose of informing yield estimates. Similar to the recommendation given in SKM (2011) with respect to calibrating HSPF models, these Sacramento models should be calibrated using objective functions that are appropriate for yield analysis in order to model inflows suitable for use as inputs to the WATHNET model. None of the rainfall-runoff models (HSPF or Sacramento) have been updated to address the issues identified by the Hydrology Expert Panel in 2010 (see Annex A of Appendix A of SKM (2011)), which were:

1. Implementing objective functions relevant for yield estimation;
2. The need to bias correct non-concurrent rainfall station records; and
3. Validated ability to model observed variability and persistence in the modelled time series of streamflow

It is recommended that rainfall runoff models are developed and calibrated that are appropriate for yield estimation. Good practice for yield estimation is to calibrate models to optimise to a combined objective function that balances several objectives. For yield estimation in the WaterNSW system, these objectives would likely be, in order of priority:

1. Minimising bias in mean annual flow (difference between modelled and observed).
2. Minimising sum of square of errors (SSE) in annual flows, as these used as the basis of the autoregressive lag-1 stochastic generation model in WATHNET (the MSSSCAR model, see Section 4.5.3).
3. Minimising SSE in monthly flows, since MSSSCAR uses the monthly pattern within each year to stochastically generate monthly inflows.
4. Minimising the SSE in daily flows. This can be undertaken using the logarithm of the flows or the flows raised to a power (say 0.5) to emphasise either the low flows or the moderate flows (no power emphasises high flows).

5. Minimising SSE in sorted daily flows, to achieve a fit to the flow duration curve. Again, log transformation or a power can be used to place more emphasis on low or mid rather than high flows.

Objectives 1, 2 and 3 can be addressed with either a monthly or daily rainfall runoff model. Potential monthly models include GR2M (Paturel *et al.*, 1995) and WAPABA (Wang *et al.*, 2011). All objectives can be addressed with a daily model, such as GR4J (Perrin *et al.*, 2003) or Sacramento (Burnash and Ferral, 1981). The degree of emphasis is placed on each objective is controlled by the weightings in the combined objective function that is used for optimisation. Common objective functions that are used for water resources planning and yield estimation in Australia include:

- Nash Sutcliffe Efficiency (NSE) with log bias constraint (Vaze *et al.*, 2010), which maximises either monthly or daily NSE, with a penalty for parameter sets with biases exceeding a few percent
- Linear Daily Exceedance and Bias (LDEB) (Egan, 2025), which typically produces minimal bias and a good fit to larger daily flows, or
- Square-root Daily Exceedance and Bias (SDEB) (Egan, 2025), which typically produces minimal bias and uses power = 0.5 to provide a good fit to moderate to low flows.

Modern software for RR calibration has almost unlimited options for combining objectives to achieve a balance across objectives that is appropriate to the modelling application.

More broadly rainfall-runoff model fits should be periodically checked and if necessary updated as more streamflow data becomes available. Contemporary good practice is to review rainfall-runoff model calibrations approximately every 5 years, depending on the stability of the calibration over time, or shortly after extreme drought events.

It is recommended that the rainfall-runoff models are calibrated so that they are suitable for informing yield estimates. Model calibration and application should be undertaken using gauged rainfall inputs and a consistent evaporation dataset. HARC has implemented a sequential calibration procedure for Sacramento where parameters are sequentially optimised using the LDEB objective function and recalibrating the lag unit hydrograph parameter as the last step using the SDEB or Power Daily Exceedance and Bias (PDEB) objective function to improve NSE and routing performance (Egan, 2025).

Given the focus on yield estimation and consideration of the experiences of estimating water yield in other water supply systems, it would be sensible to explore alternative rainfall-runoff modelling approaches. It is recommended that the monthly rainfall-runoff models, WAPABA, abcF and GR2M (Paturel *et al.*, 1995; Wang *et al.*, 2011), and daily models, GR4J and SMAR-G, be considered given the improved model performance found for another water supply system (T. Purves, Icon Water, pers. comm. To HARC 4<sup>th</sup> May 2026). The calibration of rainfall-runoff models at a monthly time step enables a focus on reproducing monthly and annual inflow statistics relevant to estimating yield, which are typically influenced by seasonal through to multi-year hydrological persistence. The decreased model complexity also allows for easier exploration of the system vulnerabilities under future changes. Calibrating daily streamflow models, included Sacramento, for monthly and annual flow metrics is also an option.

The skill and appropriateness of these models could be tested for Tallowa catchment as it is the largest catchment that relies of rainfall-runoff modelled estimates and is key to the Shoalhaven inter

basin transfers. Regardless of the rainfall-runoff model, a best practice calibration approach would involve split sample testing to check for stationarity in rainfall-runoff responses. An industry leading approach would be to implement a Bayes approach for assessing parameter uncertainty resulting from calibration of input data from different time periods (Brieva *et al.*, 2025).

The rainfall-runoff models should be robust under conditions of climate non-stationarity (WREMA and Kozarovski & Partners, 2016) given multi-decadal variability is present in the historic record (Kiem *et al.*, 2003) and the intent to use these models in climate change assessments. The calibration approach should therefore include consideration of performance under drought conditions as well as overall performance. The rainfall-runoff models need to be able to adequately represent the impacts of prolonged periods (i.e. multiple years) of decreased rainfall on antecedent conditions (independent of potential changes in catchment behaviour resulting from prolonged drought). To address these issues, the models could be calibrated to objective functions that incorporate bias during drought conditions. The model skill could be evaluated by including metrics such as the Nash-Sutcliffe Efficiency calculated using transformed values of 20<sup>th</sup> and 50<sup>th</sup> percentile streamflow to avoid biasing the model towards the skilful representation of high flow periods, and lowest system inflows over a period of n years. Adopting an objective function that also considers skilful representation of the flow duration curve could also be considered.

An option for WaterNSW to consider is to implement a new framework that capitalises on the work of Peterson *et al.* (2021a). This is where a rainfall-runoff model could be informed by a hidden Markov model of the rainfall-runoff relationship states with rainfall as a covariate that is intended to inform shifts in the rainfall-runoff relationship as a result of multi-year climate persistence. The hidden Markov model can be implemented using the R statistical package hydroState (Peterson, 2025).

In addition, more recent data and data extending further back in time to 1890 should be included provided the climate data is found to be suitable and credible for informing rainfall-runoff models aimed at informing yield estimates. It is noted that land use and land cover has changed significantly in some catchments, likely altering the runoff response. If possible, explicitly identifying the periods where catchments have undergone significant land use changes is important for selecting suitable periods for calibration and validation. Furthermore, understanding when these periods of catchment change occurred would help to distinguish these changes from other sources of inhomogeneities such as changes in data source.

If a rainfall-runoff model is found to be an accurate representation of runoff responses, it is possible that the modelled runoff could be used as inputs to the WATHNET model as it would remove anomalies resulting from changes in calculation methods, changes in land use, impacts of bushfires and climate change on the catchment response and the data inconsistencies currently affecting the existing historical inflow data set. However, it would need to be demonstrated that the rainfall-runoff model outputs are able to preserve key attributes of inflows relevant to estimating yield in order to justify preferential use of modelled rather than gauge-based inflows.

HARC advises WaterNSW to coordinate with NSW DCCEEW in order to ensure awareness of existing rainfall-runoff models for catchments in the Greater Sydney region and to identify and understand differences between the model outputs (if any).

HARC recommendation	Level of effort	Likely impact on yield assessment
#H15: Examine the suitability of different rainfall-runoff models that are conceptually better suited to informing yield estimation at monthly time step to supplement or provide alternatives to Sacramento.	Medium to high	Medium
#H16: Develop and document a rainfall-runoff model calibration strategy suitable for the purpose of yield estimation. The adopted objective functions and skill metrics should consider performance under drought as well overall performance.	Medium	Medium
#H17: Re-calibrate rainfall-runoff models to ensure suitability for yield estimation including incorporation of more recently collected streamflow data.	High	Medium
#H18: Replace existing HSPF approach used to estimate reservoir inflows for Tallowa, Fitzroy Falls, Wingecarribee and Woronora dam inflows with modelled flows from the selected rainfall-runoff model as well as regression-based flows for Nepean, Avon and Cordeaux if models are an improvement over regression equations.	High	Medium
#H19: Develop an understanding of existing rainfall-runoff models from NSW DCCEEW.	Low	Low
#H20: Seek to improve rainfall-runoff model calibration accuracy by exploring the use of at-site rainfall inputs, alternative model calibration strategies, or alternative models, with the aim to use the time series outputs from these models directly in water resources modelling if suitable calibration accuracy can be achieved.	Medium to high	Medium

#### 4.5.2.3.3 WATHNET nodal inputs

The calculations in the CMCR spreadsheet (7. CMCR\CMCR\_1961-2024\_2025 Update.xlsx) were checked for Warragamba for logical consistency. These CMCR values were based on potential evaporation inputs using calculated values, namely values derived from SILO. The following issues were identified:

- **Treatment of negative flows**

Negative flows are replaced with runoff from exposed lakebed in 22 months (2.8% of months in 64 years. Half (11) of these negative flow replacements occur in autumn (MAM), 6 in winter (JJA), 3 in spring (SON) and 2 in summer (DJF). More than half of these replacements occur in the most recent decades with 7 in the 2000s and 8 in the 2010s. The remaining occur in the 1980s (3) and the 1990s (4). The replacement of these negative calculated flows with the inflow from the exposed lake bed results in an overestimation of inflows and a breach of the mass balance. The method of replacing negative inflows in the CMCR calculations results in an additional inflow averaging 4271 ML/month for the 22 months (5% of average monthly inflows), and a total additional supply of 94GL over the 64-year record.

We recommend investigating the cause of these negative inflows. The investigation would need to include consideration of potential bias in estimated volumes of spills or releases from the reservoir, pumped inputs, and evaporation estimates. Any systematic biases would need to first be resolved before addressing the issue of negative inflows. While it is not currently the case, sequential months of negative inflows would warrant special attention. Sequential periods of negative inflows would be indicative of a systematic problem in their estimation during droughts that would result in the overestimation of yield.

For any remaining negative inflows, we recommend the use of the method developed by Szabo et al. (2022) that redistributes these negative flows in a manner that preserves mass balance as well as ensuring the derived inflows are representative of expected flow patterns

whilst avoiding the introduction of erratic flow patterns or smoothing of high recharge periods. The method by Szabo et al. (2022) informs the treatment of negative naturalised inflows resulting from storage balance calculations at a daily scale, but is adaptable for monthly calculations. The correction of negative monthly inflows derived from storage balance equations could adopt steps 3, 10-13, and 15 outlined in Szabo et al. (2022). This involves the identification of a reference gauge to inform periods of recession and low flows in the region, carrying forward of negative inflows if the reference gauge also shows low flows, identification of filling events in the calculated inflows that could be scaled down to redistribute the negative calculated inflows, and the treatment of adjustments that are identified as anomalous or due to missing data.

- **Anomalous flow found for Warragamba**

An anomalous inflow was found for August 1998 that did not use calculations consistent with the remaining CMCR calculations. It instead referred to inflows from an external spreadsheet, which is ~7% smaller than the inflow calculated using the water balance of ~890GL.

- **Comparison of CMCR and WATHNET nodal input for Warragamba**

A comparison was made between the CMCR inflows for Warragamba Dam from file “\7. CMCR\CMCR\_1961-2024\_2025 Update.xlsx”, herein referred to as “CMCR inflows” and WATHNET nodal inputs from file “\10. Hist Nodal Data Files\ Hist\_Nodal\_1909-2024\_NetEvap.txt”, herein referred to a “WATHNET nodal inflows”. A check was also made with inflows for Warragamba Dam from the file “\10. Hist Nodal Data Files\ Hist\_Nodal\_1909-2024\_EvapRain.txt” and the inflows were found to be identical to the WATHNET nodal inflows. The WATHNET nodal and CMCR inflow were found to be identical from January 1999 onwards (inclusive), as seen in Figure 6. However, the inflow differed prior to this date and appeared to be annually cyclical – WATHNET nodal inflows show the largest increases above the CMCR inflows around April and May, while the largest decreases relative to the CMCR inflows occur over the summer months.

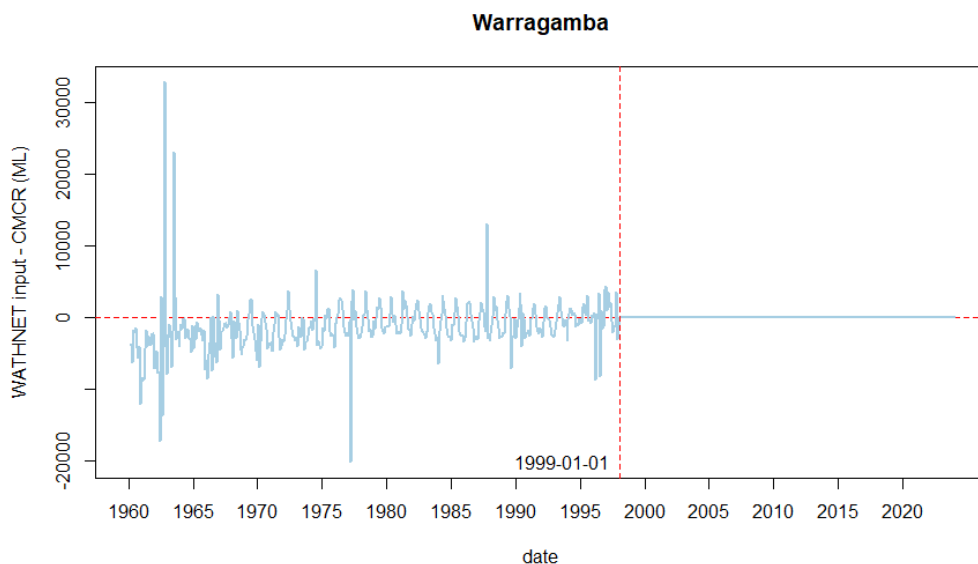


Figure 6. Time series plot of difference between the WATHNET nodal inflows and CMCR inflows for Warragamba dam for the CMCR calculated using evaporation derived from SILO.

The CMCR inflows were also calculated using pan evaporation data and a similar pattern of difference was also found, however, these differences occurred throughout the record as seen in Figure 7.

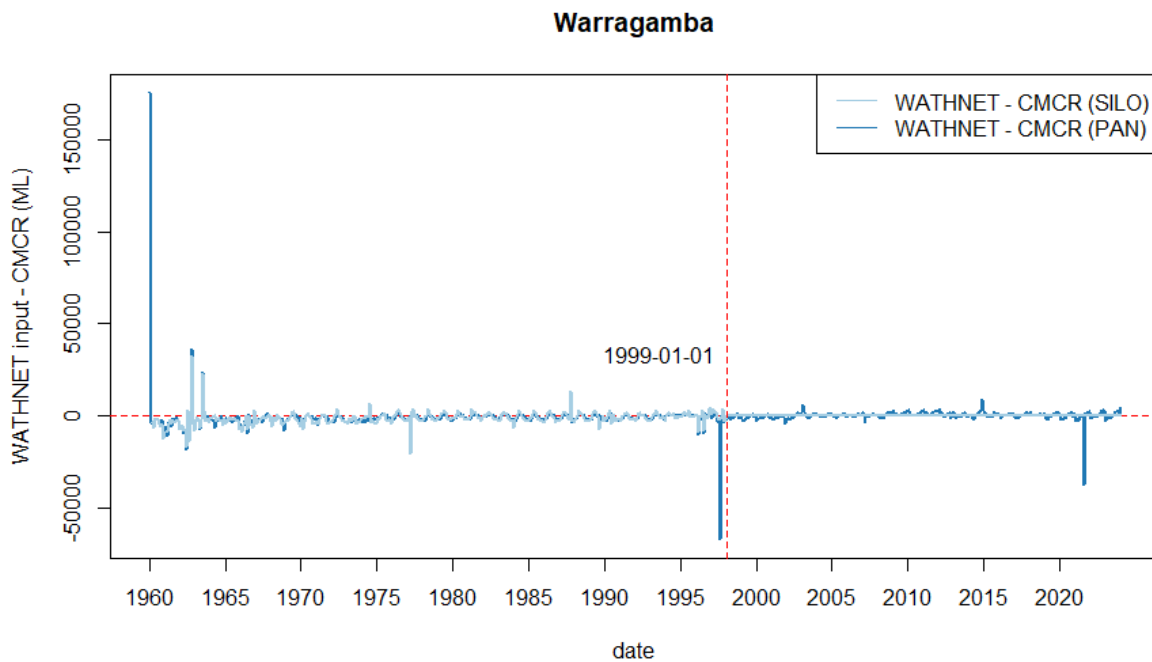


Figure 7. As per Figure 6. With the addition of the time series of plot differences between the WATHNET nodal inflows and CMCR inflows for Warragamba dam for the CMCR calculated using evaporation derived from pan evaporation data (dark blue).

An initial exploration of the provenance of the inflows is shown in Figure 6 and 7. From the figures it can be seen that the updated calculations of CMCR using SILO derived evaporation are used as inflow inputs to WATHNET from January 1999 (inclusive) onwards. As the legacy CMCR calculations were only available from December 2007 for Warragamba, it was not possible to check if those legacy CMCR calculations were used for the WATHNET nodal inflows for the period prior to January 1999.

It is noted that the climate data used for calculating the CMCR and those used as inputs to WATHNET must be consistent. In addition, there is potential to use rainfall-runoff model results to assist in identifying and diagnosing outliers in the CMCR estimates, including negative inflows.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H21: Develop and maintain documentation on the differences between the rainfall and reservoir evaporation inputs used directly in the WATHNET model and those used in the CMCR inflow calculations. This documentation should focus on differences in underlying data sources and any adjustments applied to the data prior to use. This documentation would provide clarity on whether exiting WATHNET inputs are appropriate.	Low	Low
#H22: Develop and maintain documentation on the differences between inflows calculated using legacy CMCR approaches and those calculated using the current CMCR approach. For each dam, cumulative inflow plots for the period 1960–2025 showing both legacy and current CMCR-derived inflows should be produced. These plots would assist in identifying any discontinuities or divergence in cumulative behaviour associated with changes in inflow calculation approach.	Low	Low
#H23: Investigate cause of negative inflow calculations and develop and document an appropriate treatment for negative inflows that preserve mass balance and expected flow patterns.	Low	Low

### 4.5.3 Stochastic data

As found in previous reviews, the approach taken by WaterNSW in generating synthetic input sequences for supply system modelling using WATHNET is, in general, consistent with contemporary good practice in industry. The approach is understood to be most suitable for assessing system performance where short to medium term influences dominate the system. However, for systems that are designed to operate in periods of multi-year droughts, the preservation of long-term persistence becomes increasingly relevant for assessing more extreme system metrics such as the system security (specified in the WaterNSW Operating Licence 2024-2028). Section 7 of Sinclair Knight Merz (2003) previously provided a detailed review of literature on the suitability of different stochastic simulation approaches relevant to assessing reservoir system performance.

#### 4.5.3.1 Reconciling stochastic and historical data

The chaotic nature of weather processes means that historical climate records are a single realisation of weather events even under stationary climate and catchment conditions. Synthetic climate data can be stochastically generated to preserve key attributes of the historical data, including, for example, mean, variance, temporal lags, and dependencies across multiple sites. The generation of many climate replicates means that there is potential to explore the impacts of statistically plausible event sequences that have not been observed in the historical record, such as severe droughts.

A sufficient number of replicates is required to produce a stable estimate of the system yield, namely when the use of additional runs using stochastic data inputs do not markedly change the yield estimates. The number of replicates required to achieve this stability is dependent on the system complexity. The length of the replicates should be equal to the historical record, which would enable a validation (if desired) of the reliability and duration criteria for yield that are calculated using stochastic data against that of the historical yield.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H24: Determine the number of replicates needed under historical climate conditions to achieve a stable estimate of yield.	Medium	Low

#### 4.5.3.2 Replicate attributes

The MSSSCAR algorithm generates stochastic data for each stochastic replicate by defaulting to initialising the stochastic generator with median values of each variable. The initial conditions therefore typically influence the first year or two of each replicate, with minimal influence on the remaining years of each generated replicate. Conceptually, the system yield calculates the demand that would be supplied that complies with the specified performance criteria over the long-term, so the desired outcome for yield estimation is that the influence of initial conditions should be minimal. For yield estimation, ideally MSSSCAR would be applied to generate only one very long replicate, so that initial conditions have the least possible influence on the generated data. Based upon the sample replicates provided by WaterNSW, it appears that data was generated for 100 replicates each of 10,000 years. The method applied to generate the data in the sample input files is therefore close to optimal, in terms of reducing the influence of the initial conditions on the data for each replicate and hence the yield estimates..

HARC recommendation	Level of effort	Likely impact on yield assessment
#H25: For yield estimation, adopt the minimum number and maximum length combination permitted by the WATHNET software (MSSSCAR) (ideally one very long replicate). Confirm that this has minimal influence on calculated yield, compared with the adopted number and length of replicates (currently 100 replicates each of 10,000 years).	Low	Low

#### 4.5.3.3 Assumption of stationarity

Within the file “\14. Stoch Nodal\Stoch 1909-2024\10k\_100yr\_1909-2024\_EvapRain” it is noted that the calibration data used to generate the stochastic data was from: “\10. Hist Nodal Data Files\Hist\_Nodal\_1909-2024\_EvapRain.txt”.

The whole historical time series spanning from 1909-2024 was used to calibrate the parameters and disaggregate the annual simulated data. The stochastic data generated in this case assumes stationarity in rainfall runoff processes and in the runoff record. It is noted that land use and land cover has been stated to have changed significantly in some catchments, but analysis specific to identifying historical stationarity is unavailable. In addition, the SKM (2011) review noted that the streamflow estimated from regression models exhibited low variability and should not be used to calibrate parameters for the stochastic data generation model. Documenting the potential sources of non-climatic streamflow signals would be valuable to distinguish between effects from real sources of changes in the rainfall-runoff relationship, such as changes in land use, climate-induced catchment responses, or bushfires, compared with artificial sources, such as changes in data inaccuracies or changes in calculation methods. Statistical tests to identify periods of near-homogeneity should be undertaken as part of the process to develop unbiased inputs for generation of stochastic data. It is possible that if skilful rainfall-runoff models can be developed that results from these could also be used to diagnose discontinuities in the composited inflow time series.

To test if calibration is appropriate, a split sample test should be implemented. The results of Kiem et al. (2021) identified a clear decreasing trend in streamflow in Warragamba, Avon, and Shoalhaven catchments corresponding to warming temperatures post 1990. A split sample test would therefore be more likely to be successful if a temperature covariate was adopted in the model.

Split sample testing could also be applied to contiguous subsets of the composite inflow record with the subsets defined by the method or datasets with which they were derived (e.g. CMCR, rainfall-runoff modelling, transposed flows). The split sample testing would identify whether different subsets of data would result in statistically significant differences in the parameterisation of the stochastic generator. The differences in these subsets could be addressed using an established method of Bayesian data augmentation that can, in principle, be applied to composite records. Although this approach has not been widely applied in statistical hydrology, the approach is defensible and applicable to the nature of the inflow data used here. The main effort would be developing scripts to implement the data augmentation algorithm and developing a suitable probability model of the unexplained variability in rainfall-runoff or regression estimates of annual or seasonal flows.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H26: Ensure calibration of stochastic simulation parameters is based on a period of rainfall-runoff behaviour that is reasonably free from non-	Medium	Medium

HARC recommendation	Level of effort	Likely impact on yield assessment
climatic signals. Addressing this recommendation is dependent on addressing recommendations in Section 4.5.2.		
#H27: Consider the development and implementation of Bayesian data augmentation to address differences in subsets of the composite inflow records to reconcile these time series.	Medium	Low

#### 4.5.3.4 Single season assumption

The selection was made to use a single season in the stochastic generation with the season defined by the calendar year (January to December). The assumption of a single season appears to be acceptable based on the plot of monthly average inflows as a fraction of the annual average (Figure 8). It is also recognized that the use of annual lag-one autoregressive models coupled with temporal disaggregation for multi-site systems, as used here, has historically been the a preferred approach (McMahon et al. (1996) in Sinclair Knight Merz (2003)).

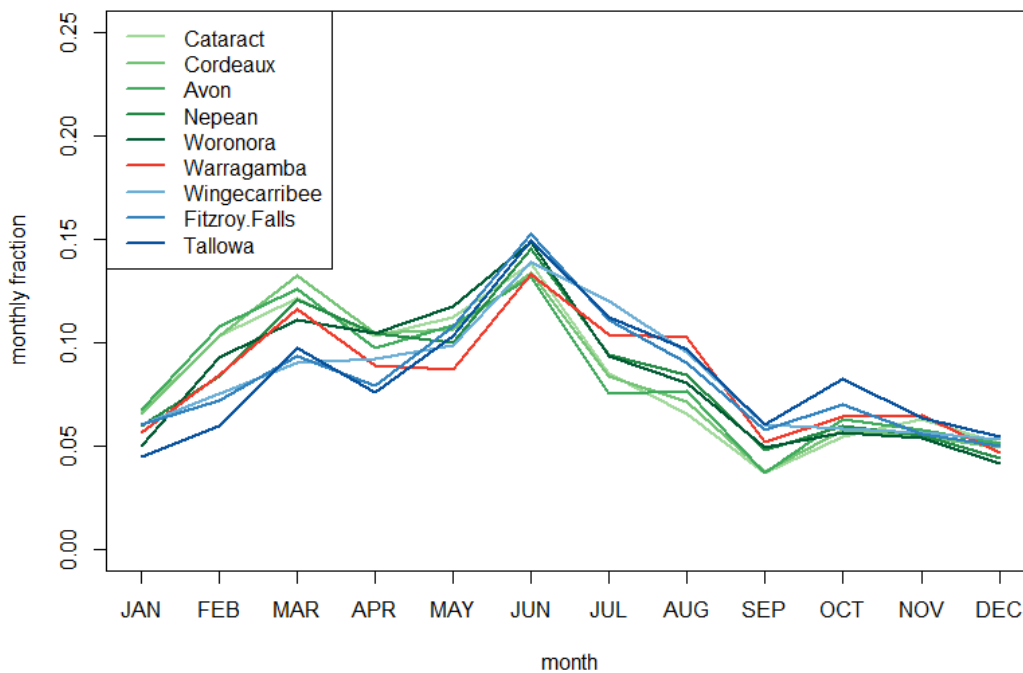


Figure 8. Average monthly inflows as a fraction of the annual average for the Warragamba, Metro, and Shoalhaven dams. Inflows from \10. Hist Nodal Data Files\Hist\_Nodal\_1909-2024\_EvapRain.txt

The assumption of the single season aligned with the calendar year is broadly applicable to most of the inflows. For the purposes of stochastic data generation, the definition of the ‘water year’, defined as starting in the month with the smallest average inflow, commences in December for five of the dam locations these being Warragamba, Nepean, Woronora, Wingecarribee, and Fitzroy Falls Dams and January for Tallowa Dam. The month of lowest mean inflow September for three dams, these being Cataract, Cordeaux, and Avon Dams, suggesting that for these dams, the monthly pattern within a stochastically generated ‘water year’ may be fragmented. However, the inflows from September to December are relatively small at these dams compared with other months, so the impact of fragmenting these monthly temporal patterns is unlikely to have a significant effect on stochastic data or yield outcomes.

There are several local minima throughout the year where a partition into two or three seasons per year could be justified, for example December – March, April – August, and September-November. The partitioning of seasons could be justified given the seasonally varying impacts of the El Niño Southern Oscillation (spring and summer), the Southern Annular Mode (spring), and blocking highs (autumn) on seasonal rainfall. The definition of seasons would require a more thorough examination of the inflows as well as climate variables that are stochastically generated than the initial examination shown here. The examination of different seasonal definitions should also occur in conjunction to the exploration of using values of  $k > 1$  (as per Section 4.5.3.5). It is critical that the stochastically generated data can preserve multi-year persistence regardless of the seasonal definition adopted.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H28: Explore the impact of using multiple seasons on the statistical attributes of the synthetic data and adopt an appropriate seasonal definition.	Medium	Low

#### 4.5.3.5 k nearest neighbours

The annual values in the first step, which are then disaggregated to a monthly scale using the method of fragments with the monthly pattern informed by the historical year selected using the kNN algorithm. The nearest k years are determined by the Mahalanobis distance, which is a unitless and scale-invariant measure suitable for measuring distances that are comparable between different variables. A selection is made by sampling the year from a trapezoidal probability distribution of the k nearest neighbours, where decreasing weights of k to 1 are assigned by increasing distance to the k nearest years.

The selection of  $k = 1$  results in the closest historic year always being selected to inform the monthly distribution of the generated values resulting in greater uniformity in the monthly temporal patterns generated. This uniformity will be most noticeable in the generated annual values that are less than the historical minimum (i.e. dry years) or greater than the historical maximum (i.e. wet years). However, it can be seen from Figure 9 that the monthly temporal patterns of the driest ten inflow years at Warragamba are variable and the selection of  $k = 1$  would result in only the driest temporal pattern being sampled for stochastically generated years that are near or drier than the driest year.

The use of larger k values would allow for greater sub-annual variability but can reduce the ability to reproduce persistent water supply shortages in systems sensitive to sub-seasonal variability. An alternative or addition approach to increasing the value of k is through the use shorter seasons (recommendation #H30). Adopting shorter seasons (e.g. two six-month-long seasons or three four-month-long seasons) would in itself introduce more inter-seasonal variability and reduce the influence of the kNN algorithm. By adjusting both the k value and the season definition could allow both the preservation of seasonal variability and variability in temporal patterns for dry years in the stochastically generated data.

In considering what value of k to adopt the following should be considered:

1. Selecting a value of k represents a trade-off between having more month-to-month variability within a year and potentially having month-to-month variability sampled from an observed year that is not climatically or hydrologically similar to the stochastically generated year (e.g. if the

value of k is too large a historically temporal pattern from an average year may be used to inform a very dry stochastic replicate).

2. The WATHNET user guide suggests an appropriate value for k is  $\sqrt{N}$  where N is the number of observed years. In this case where we have 116 years of data, so a k value of 11 would be consistent with this guidance.
3. As more inputs are generated in WATHNET there is an increased chance of temporal patterns being applied to years which are not climatically or hydrologically similar. The amount of variability in temporal patterns for a single input, when generating stochastic data for many inputs may be worth investigating further. For example, WaterNSW may wish to investigate if and how often a “wet” year temporal pattern is applied to disaggregate a “very dry” year.

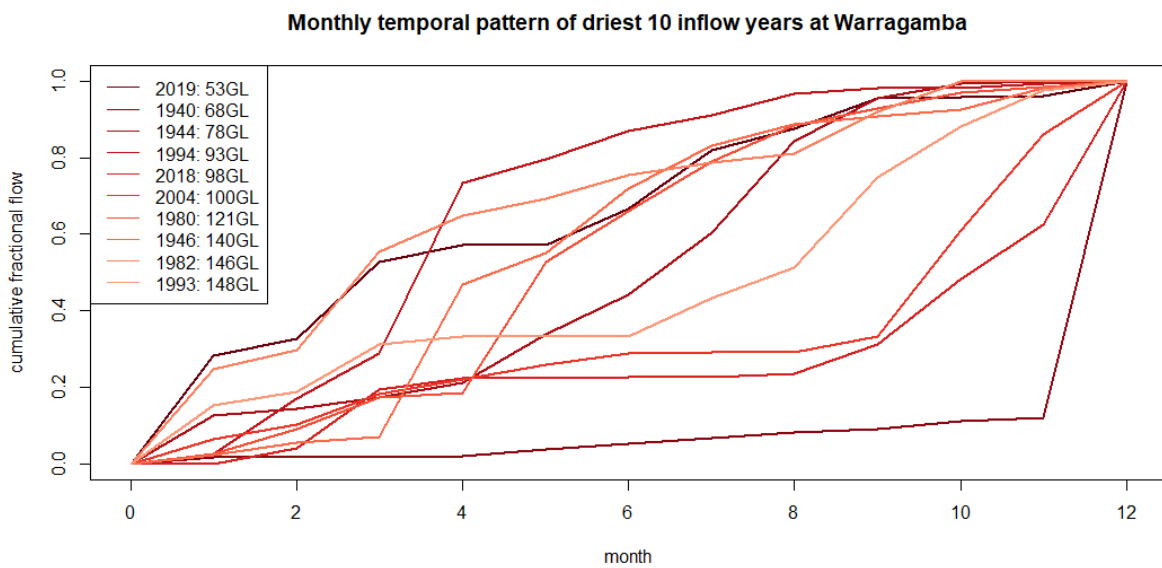


Figure 9. Monthly temporal patterns of inflow at Warragamba for the driest ten years.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H29: Generate synthetic data using k = 5 and k = 11 and investigate the prevalence of monthly temporal patterns for near-average or “wet” years being applied to synthetic low flow years as well as ensuring a variety of temporal patterns from dry years are being sampled.	Medium	Unknown
#H30: Examine the impact of using k = 5 and k = 11 and different season definitions on the metrics of system performance.	Medium	Unknown

#### 4.5.3.6 Correlations, lags, and covariates

No covariates were used for regression modelling. It is highly likely that a climate covariate would need to be introduced as part of creating a stationary reference climate series for the stochastic data generation. This is discussed further in Section 5.6.1 in the context of historical climate change, with a relevant recommendation to examine whether a covariate is needed to create a stationary reference climate series.

For all sites, a lag of 1 resulted in the minimum AIC value. The Sinclair Knight Merz (2003) review indicated that the influence of explicitly modelling long-term persistence on system performance was likely small relative to other uncertainty considerations. However, the development of long-memory models has developed since the 2003 review. Advancements have included the use of hidden Markov

models (Thyer and Kuczera, 2003) and wavelet autoregressive models (Kwon *et al.*, 2007; Steinschneider and Brown, 2013). The impacts of long-memory models on assessing yield compared to shorter memory models has yet to be demonstrated but is a worthy avenue of exploration particularly given the prevalence of persistent droughts in the region.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H31: Explore the impact of long-memory models for stochastic data generation.	Medium	Low

#### 4.5.3.7 Paleoclimate informed stochastic data

At present, paleoclimate informed stochastic data has not been used in the WATHNET model. The use of paleoclimate-informed stochastic data would enable the exploration of plausible long-term climate persistence. Paleo-informed stochastic data based on low frequency variability in the Interdecadal Pacific Oscillation is available for locations within NSW for daily variables of rainfall, potential evaporation, and potential evapotranspiration spanning 131 years (NSW Government, 2026). Paleo-informed stochastic data was previously generated by the University of Newcastle to support components of the 2022 Greater Sydney Water Strategy, primarily described in the strategy as 'bookend' type analysis. In parallel, the University of Adelaide has generated paleo-informed stochastic data for NSW DCCEEW across most of NSW, and the datasets used in that process have recently (in late 2025) been adopted as a Common Planning Assumption by NSW Treasury. Those datasets, as linked from the NSW Treasury website to the NSW Government's online SEED database, do not yet include datasets for the Greater Sydney region.

Issues identified by the metropolitan climate change working group associated with adopting the DCCEEW datasets include the reliance on the use of rainfall-runoff models because runoff is not generated in the datasets by DCCEEW to date, while rainfall is. In addition, there would a need to generate paleo-stochastic temperature data if Sydney Water's current demand model configuration is to be retained as it currently uses air temperature data, not the PET data that has been generated by DCCEEW.

The existing paleo-climate datasets cannot be directly adopted by WaterNSW because only 10,000 years of data has been generated, which is not enough to assess low likelihood event behaviour relevant to WaterNSW's level of service objectives for reliability of supply.

Alternatively, the DCCEEW methods could be adapted to generate paleo-stochastic inflows rather than using the existing paleo-informed stochastic rainfall as inputs to rainfall-runoff models. Generating paleo-stochastic inflows is the preferred option as it avoids the use of rainfall-runoff models, which introduces an additional source of uncertainty, enables the generation of a data set with a length suitable for assessing low likelihood event behaviour relevant to assessing water supply reliability, and allows for efficient updating of the model as more instrumental data becomes available. The paleo-informed stochastic data generation model has three hierarchical levels:

1. The first level is based on an alternating sequence of Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO) positive and negative epochs whose length is sampled from a gamma distribution whose parameters are informed by paleoclimate methods that reconstruct IPO epochs over 440 years (Henley *et al.*, 2014).

2. The second level then samples annual values from a multi-site autoregressive model conditioned on the IPO/PDO epoch (either wet or dry).
3. The third level then disaggregates annual values.

The WATHNET stochastic model supports this framework and was previously tested for the Sydney system by Zhang (2018). This thesis allows WaterNSW to rapidly evaluate the paleo-informed framework using streamflow and if this approach is pursued by WaterNSW, reviewing Zhang’s thesis is strongly advised. One of the findings by Zhang (2018) was that uncertainty in the paleo-informed parameters for the gamma distribution had little impact on risk-based security metrics. What did have a major impact was the uncertainty in the autoregressive model parameters for wet and dry IPO epochs – splitting the instrumental record into wet and dry IPO epochs effectively halves the number of samples to estimate parameters.

If preparing yield estimates to support submissions to NSW Treasury, there is a risk that the use of stochastic datasets that do not align with DCCEE’s methods could result in delays or difficulties in obtaining approvals. HARC recognises that this is a recent development and that it could take many months for WaterNSW to transition to a stochastic data generation that aligns with this Common Planning Assumption. This transition period provides an opportunity for WaterNSW to seek approval from NSW Treasury and NSW DCCEE to adopt the paleo-informed stochastic approach used to generate stochastic data for NSW DCCEE and apply it to the generation of paleo-informed stochastic inflow data.

HARC recommendation	Level of effort	Likely impact on yield assessment
#H32: Use available paleo-stochastic climate data as inputs to yield estimation that aligns with NSW Treasury Common Planning Assumptions. This recommendation is dependent on either addressing rainfall-runoff modelling recommendations or generating paleo-stochastic inflows that are considered consistent with the NSW Treasury Common Planning Assumptions as well as addressing Sydney Water demand modelling needs. Alternatively, a preferred recommendation is to generate paleo-stochastic streamflow data using the same methods as NSW DCCEE for generating paleo stochastic climate data.	High	Medium

#### 4.5.3.8 Application in WATHNET model

From the stochastic nodal files supplied combined with the Hydrology Memo, it appears that system yields have been assessed by using WATHNET inputs of 20 000 replicates of 50-year periods segmented from 100 replicates of 10 000 years of synthetic data.

Previously, simulations of synthetic data used 10 000 replicates of 111 years in length, which reflected the length of historical data available at the time. Typically, simulations using stochastic data are run for a time period identical to the historical data in order to ensure that metrics are being assessed over a comparable time period and that anomalies are not introduced as a result of a difference in the duration considered.

The review by Kuczera (2025: 29) presumed that the motivation for using 50-year replicates was to run dynamic (transient-state) simulations where the initial conditions would be static, but the impacts of increased demand with time would be explored.

The use of long simulations that are then segmented into 50-year segments are appropriate inputs for estimating yield provided yields estimated using synthetic data are first validated using replicates with record lengths equal to the historical data. Dynamic simulations that examine the impacts of climate change on both demand and supply would be beneficial for exploring drought management plans, providing more realistic projections of near and medium-term conditions, and exploring the impact of hypothetical augmentation systems and trigger levels. Such simulations could also help to address questions of when to invest in supply augmentations. Dynamic simulations could also examine whether current storage levels influence yield estimates and motivate discussions on how current storage levels could be used to assess water security risks in the near term.

## 5. Review of the climate change impact on system yield analysis

### 5.1 Introduction to the climate change review

This aspect of the independent review covers how WaterNSW's model, modelling and processes for determining the system yield consider the impacts of climate change. Under Clause 35(2) of its operating licence, WaterNSW must "consider the impacts of climate change" when it is determining or re-determining the system yield (IPART, 2024).

This review of climate change impact assessment modelling and processes includes the review scope (Section 5.2), the information that HARC received for the review (Section 5.3), a quick recap of previous reviews (Section 5.4), HARC's understanding of the WaterNSW approach (Section 5.5) and the HARC review findings and recommendations (Section 5.6). Stakeholder feedback on this aspect of WaterNSW's model, modelling and processes is summarised in Section 5.3 and the outcomes of any consultation by HARC with WaterNSW to clarify information during the review is captured in Sections 5.5 and 5.6.

### 5.2 Scope of the climate change review

The scope of works for this aspect of the WATHNET model review was outlined in the WaterNSW Statement of Work (WaterNSW, 2026a) and seeks to:

1. "Critically review the climate change impact methodology adopted to determine the impact to system yield, including any implications for water security analysis because of assumptions adopted for the method.
2. Propose refinements or alternative approaches in consultation with WaterNSW and determine the resulting climate impacted yield.
3. Advise on the suitability of the climate affected yield estimates for water supply planning, including considerations for limitations and uncertainty."

Consistent with the other elements of the review of system yield, based on the WaterNSW operating licence requirements (IPART, 2024), the review must ensure the modelling framework is robust and reflects good industry practice, identify improvement opportunities in model structure, assumptions, and yield estimation methodology, and consider stakeholder feedback.

### 5.3 Information HARC received for the climate change review

HARC received the following information from WaterNSW for this aspect of the review:

- WaterNSW (2023) *Climate Change Impact Assessment for Greater Sydney Water Supply System Using NARClIM1.5 data*. March 2023 – This document is a description of the methods used by WaterNSW in 2023 to assess the impact of climate change on the system yield to support the Long Term Capital and Operational Plan (Sydney Water, 2024a).
- Sample input datafiles to the WATHNET model under an example climate change scenario.
- *WaterNSW Rainfall-Runoff Model Development – Memo for 2026 WATHNET Model Review* – This document provided additional information on how WaterNSW uses its rainfall-runoff

models to calculate climate change factors for its inflows. Rainfall-runoff models and their draft calibration reports were also provided for the Cataract Dam and Warragamba Dam catchments.

- Sample climate change demand factors (originally from Sydney Water) and related correspondence from Sydney Water, as well as a WaterNSW undated file note titled *Climate Linked Demand Factors* – This information outlined the process for factoring demands under projected climate change.
- A summary list of assumptions currently being used by WaterNSW for climate change impact assessment, relative to the assumptions used in the 2023 assessment.

The approaches adopted by WaterNSW for rainfall-runoff modelling and climate change impact assessment have also previously been summarised publicly in conference papers (Raut *et al.*, 2022; Maheswaren *et al.*, 2023).

The following documents were provided by NSW DCCEEW to add further context for the review of climate change impact assessment approaches being applied by the NSW Government:

- *Draft Framework for Selecting and Preparing Climate Change Data for hydrological modelling purposes* (DCCEEW (NSW), 2026a) – This document presents DCCEEW's draft steps and some key assumptions when preparing climate change datasets for hydrological modelling, consistent with its approaches for recent Regional Water Strategies
- File note on assessing the suitability of NARClIM1.5 and 2.0 for hydrological modelling (DCCEEW (NSW), 2024).

The following documents were provided by Sydney Water, which collectively outline Sydney Water's position on selecting climate scenarios and adaptation measures:

- *Climate Change Adaptation Guidebook* (Sydney Water, 2024b)
- *Position Statement: Climate Change Adaptation* (Sydney Water, 2024c)

The following documents were publicly sourced from NSW Treasury to understand Treasury's position on climate change impact assessment requirements:

- *NSW Government Business Case Guidelines. TPG24-29* (NSW Treasury, 2024a)
- *Resilience. TPG24-29 NSW Government Business Case Guidelines – Technical Note* (NSW Treasury, 2024b)
- *NSW Government Guide to Cost-Benefit Analysis* (NSW Treasury, 2025)

HARC facilitated a stakeholder workshop on 24<sup>th</sup> February 2026 to provide an overview of our role on the review and to document stakeholder feedback about WaterNSW's model, modelling, and processes for determining the system yield. In addition to WaterNSW and HARC, the workshop was attended by representatives from NSW DCCEEW, Sydney Water, IPART, the Sydney Desalination Plant, some water supply customer councils, and NSW Treasury. HARC also had discussions with WaterNSW and Sydney Water to clarify details around current approaches to the climate change impact assessment.

## 5.4 Previous reviews of WaterNSW climate change impact assessment

Prior to the WREMA (2021) review, climate change was only considered with respect to the potential capability of the WaterNSW model to consider climate change, the suitability of climate change data for assessing yields, and the suitability of rainfall-runoff models for modelling climate change impacts. The WaterNSW WATHNET model was found to be suitable and capable of assessing changes in yield estimates resulting from climate change (SKM, 2011; WREMA and Kozarovski & Partners, 2016).

The WREMA and Kozarovski & Partners (2016) review considered the climate change data (at that time) to be of insufficient quality to provide reliable estimates of climate change impacts due to the regional modelling and downscaling approaches used at the time. Recommendations on future climate change considerations were also provided. It was documented that climate change data would need to be appropriately bias corrected and that key statistical attributes such as persistence are preserved to be suitable for assessing yield under climate change. In addition to the data suitability concern, the review also documented the lack of consensus on methods suitable for assessing climate change impacts on yield estimates.

The WREMA (2021) review discussed a number of approaches for considering climate change. The report raised concerns regarding methods that used relatively short records, in the order of 20 years, for estimating change factors due to increased sampling error associated with smaller samples. A preliminary assessment of climate change impacts using covariate analysis from Kiem et al. (2021) was presented for Warragamba streamflow in the final WREMA (2021) report. In this demonstration, air temperature was used as a covariate when stochastically generating streamflow data. When the year 2020 level of warming was adopted in the co-variate analysis, there was a 16% reduction in yield relative to using the instrumental record data. While the review recognised that climate change needed to be considered in yield assessments, a prescriptive approach for future assessments was not made given the recognition that numerous plausible and defensible approaches exist for assessing climate change impacts on system yield.

In considering how future planning could be informed, the expert panel for the WREMA (2021) review recommended the use of dynamic (transient-state) simulations to assess water security over the planning horizon. A transient-state simulation from current system conditions would allow the effects of non-stationary demands and non-stationary hydroclimate (i.e. climate change) to be considered in the analysis, which can be important for systems such as the Greater Sydney supply system, with large storage capacity relative to demands.

The expert panel consulted for the WREMA and Kozarovski & Partners (2016) stressed the need for rainfall-runoff models to be robust under conditions of non-stationarity in order to be appropriate for modelling climate change impacts.

The WREMA (2021) review also documented the need to consider climate change uncertainties in the Drought Management Plan.

### 5.4.1 Summary of previous climate change review outcomes

From these previous reviews of climate change considerations in WaterNSW's water resource modelling, the following conclusions were drawn:

Table 5-1 Previous climate change review outcomes and HARC identification of WaterNSW response

Recommendation	HARC identification of WaterNSW response
WATHNET found to be suitable and capable of assessing changes in yield estimates resulting from climate change	Not applicable
Climate model projection data needs to be appropriately downscaled and checked for key statistical attributes	WaterNSW checked this in its 2023 assessment (see Section 5.6.6 and 0 of this review)
The use of relatively short records (20 years) to calculate climate change factors is likely to be problematic	WaterNSW has since adopted 30-40 year time slices (see Section 5.6.10.1 of this review)
The use of annual temperature as a covariate is an example of a defensible approach to assessing climate change impacts on system yield	This has been tested for Sydney's water supply catchments. HARC's view is that this approach is well suited to addressing non-stationarity in historical observations due to global warming and for providing a second line of evidence of the impact of climate change on yield.
The influence of climate change is one motivator for considering transient-state water resource modelling	WaterNSW undertakes transient-state modelling using demands that increase over time due to population growth. WaterNSW has not incorporated incremental climate change over time into this transient-state modelling. HARC's view is that techniques that can incorporate non-linear climate change trends over time (e.g. pattern scaling – see Section 5.6.10.2 of this review or co-variate analysis – see Section 5.6.6 of this review) are marginally better suited to transient-state modelling than existing WaterNSW techniques, but that existing techniques would not limit the ability to implement transient-state modelling that incorporates the effects of incremental global warming over time. The inclusion of incremental climate change into transient-state modelling is still in its infancy within the Australian water industry.
Rainfall-runoff models need to be robust under conditions of non-stationarity in order to be appropriate for modelling climate change impacts	This is an ongoing area of investigation by both WaterNSW and DCCEE. HARC notes that a recent assessment of annual rainfall-runoff non-stationarity in northern NSW, which was unable to attribute identified non-stationarity to climate influences, potentially complicates this issue for application in the Sydney water supply catchments (see Section 5.6.1 of this review).

## 5.5 HARC understanding of WaterNSW approach

### 5.5.1 2023 approach

The modelling approach for climate change impact assessment that was undertaken by WaterNSW in 2023 to support the *Long Term Capital and Operational Plan* (Sydney Water, 2024a) is documented in its methods report (WaterNSW, 2023). HARC's understanding of that approach is summarised as follows.

**Historical rainfall stationarity and climate change:** Examination of historical rainfall datasets for stationarity from 1890 onwards through the use of cumulative mass curves over the period of the instrumental record and the calculation of mean values over periods of increasing or decreasing

cumulative mass. It was concluded by WaterNSW from this analysis that there was no trend in catchment rainfall for the Warragamba Dam catchment.

**Historical PET/temperature stationarity and climate change:** Examination of historical annual air temperature data for stationarity from 2006 onwards using a line of best fit through that data. It was concluded by WaterNSW from this analysis that there was an increasing trend in air temperature from 2006-2021 at the two weather stations analysed. Potential evaporation (PET) trends were not assessed due to gaps in the data.

**Rainfall-runoff model calibration:** Calibration of Sacramento models for seven dam catchments, with various sub-area models within each catchment that have unique parameter sets. The rainfall-runoff models were calibrated using AWAP gridded rainfall. The grids were used to generate catchment average values for each time step (Raut *et al.*, 2022).

**Climate change data source:** The climate change impact assessment methods report utilised the NARClIM1.5 datasets available at that time. The bias-corrected NARClIM datasets were used.

**Emissions pathway selection:** WaterNSW used the two available emissions scenarios from NARClIM1.5 (RCP4.5 and RCP8.5).

**Climate model selection:** WaterNSW processed the outputs from all available NARClIM1.5 models. For reporting purposes, WaterNSW also reported a median climate change from all available NARClIM1.5 projections. WaterNSW has not yet reported changes in supply system yield under projected climate change.

**Climate model output checks:** A range of checks were undertaken to compare raw and bias-corrected climate model outputs, and to compare either of these datasets against observed (or observed gridded) data. This included presenting average annual gridded rainfall data to understand climate model biases in rainfall before and after bias-correction, daily rainfall exceedance curves, annual rainfall distributions, annual PET exceedance curves, annual PET distributions, and the frequency of rain events of durations from 1-5 days.

**Spatial averaging of climate change impacts:** Catchment average climate model outputs were generated by overlaying rainfall-runoff model sub-catchment boundaries onto the NARClIM1.5 grid cells to calculate a climate model output value averaged spatially across the catchment.

**Supply system behaviour using observed data versus climate model outputs:** Several comparisons were presented between WATHNET model inputs/outputs based on the observed data and when using the NARClIM1.5 outputs to generate WATHNET model inputs/outputs over the climate reference period from 1980-2019. This 40-year period was the reference period used to generate the climate change scaling factors.

**Climate change scaling factors including climate reference periods:** For its climate change scaling, WaterNSW used a time slice method with the following 40-year time slices:

- Historical period (1980-2019, centred on the year 2000)
- Near future period (2020-2059, centred on the year 2040)
- Far future period (2060-2099, centred on the year 2080)

For each time slice a linear relationship was fitted between the ranked bias-corrected climate model outputs over the historical time slice and for a future time slice. A simple example is illustrated in Figure 10 for spring PET for the Warragamba Dam catchment from a single climate model and emissions scenario. This process was also undertaken using Sydney Water’s demand model outputs and WaterNSW’s rainfall-runoff model outputs, when using climate inputs factored for projected climate change. For each variable, scaling factors are derived for four seasons (spring, summer, autumn, winter). The runoff variables were log-transformed before fitting a linear relationship through the data.

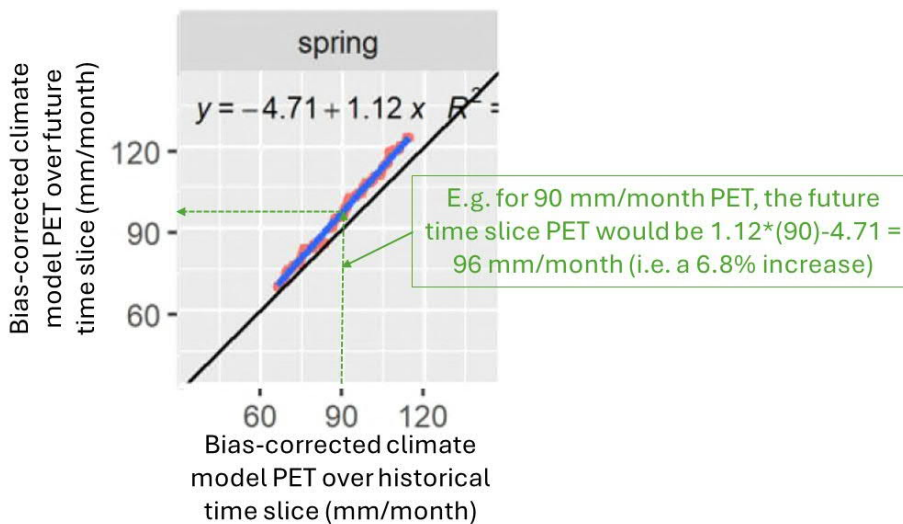


Figure 10 Example relationship between historic modelled and future modelled PET for a given future time slice. The red dots are the climate model outputs, the blue line is the fitted relationship, and the black line is a 1:1 relationship representing no climate change. Source: (WaterNSW, 2023) with annotations by HARC.

**Climate change impact on demands:** Sydney Water undertakes the demand modelling of the Greater Sydney supply system, including the calculation of climate change scaling factors to apply to the WATHNET model demand disaggregation factors. This process is understood by HARC to involve inputting climate variables into Sydney Water’s demand models that have been scaled for projected climate change using the NARCLiM projections, then taking the demand model outputs to calculate updated WATHNET model demand disaggregation factors under the climate scenario being assessed, for four demand regions. These adjusted demand disaggregation factors are then provided to WaterNSW. Demand disaggregation factors are provided for each month within 40-year time slices, consistent with the time slices used in WaterNSW’s scaling approach at the time (see above). WaterNSW then takes these scaling factors, groups them according to the season of the year (4 seasons) and fits a regression relationship between the pairs of demand disaggregation factors under historical and future climate conditions.

### 5.5.2 2026 approach

Key assumptions for the climate change impact analysis that is currently being undertaken by WaterNSW, relative to the 2023 analysis, are listed in Table 5-2. Details on the 2026 approach were provided by WaterNSW (A. Breda, WaterNSW, pers. comm. to HARC 10<sup>th</sup> March 2026). Key changes were:

- NARCIIM2.0 projections adopted instead of the NARCIIM1.5 projections.
- Bias-correction of the PET projections by WaterNSW, rather than using the NARCIIM bias-corrected PET projections.
- Use of SSP3-7.0 (the highest emissions pathway available from NARCIIM2.0) instead of RCP8.5 (the highest emissions pathway available from NARCIIM1.5). SSP2-4.5 aligns with the previous RCP 4.5.
- Shifting of the historical climate reference period, when preparing climate change scaling factors, to end in 2025, and a shifting of the mid-century future time slice from 2040 to 2050.
- 30-year time slices instead of 40-year time slices, when calculating climate change scaling factors.

Table 5-2 Summary of key assumptions and methods for WaterNSW climate change impact assessment in 2023 and 2026

Aspect	2023 approach for LTCOP	2026 approach (provided by WaterNSW)
Historical data stationarity checks	Cumulative mass curves, mean values over different multi-year periods, linear regression	Analyses extent not confirmed to HARC at time of review
Climate projection data source	NARCIIM1.5 bias-corrected projections	NARCIIM2.0 bias-corrected projections for rainfall NARCIIM2.0 raw projections for PET, bias-corrected using transformation functions for each season
Emission pathways	RCP4.5, RCP8.5	SSP2-4.5, SSP3-7.0, with SSP1-2.6 as a lower priority
Climate scenarios	All available NARCIIM1.5 projections (6 per SSP)	All available NARCIIM2.0 projections (10 per SSP)
Climate model output checks	Comparison of NARCIIM and observed data over historical period (gridded averages, exceedance curves, annual distributions, rain event frequency)	Comparison of NARCIIM and observed data over historical period (gridded averages, exceedance curves, annual distributions)
Spatial analysis	Calculate catchment average values of the projections	Same approach
Climate scaling method	40-year time slices	30-year time slices
	Climate reference period 1980-2019	Climate reference period 1996-2025
	Future time slices 2020-2059 2060-2099	Future time slices 2040-2069 2070-2099
	Linear regression fitted through scatter plot of monthly values for climate reference period vs future time slice to generate scaling factors	Linear regression fitted through scatter plot of monthly values for climate reference period vs future time slice to generate scaling factors. Outliers removed where they had high leverage on the regression model fit.

Aspect	2023 approach for LTCOP	2026 approach (provided by WaterNSW)
Rainfall-runoff modelling for climate change impact assessment	Sacramento models calibrated to 2007-2019 (Cataract) and 1991-2019 (Warragamba) using AWAP gridded climate inputs.	Used the same models from the 2023 study
Inflow scaling method	Linear regression fitted through scatter plot of rainfall-runoff model values for climate reference period vs future time slice to generate scaling factors	Same approach
Demand derivation under projected climate change	Demand modelling by Sydney Water. Demand model used NARClIM climate projections to generate demand factor in each month of each future time slice, for 11 demand nodes.	Demand modelling by Sydney Water. Demand model used NARClIM climate projections to generate demand factor in each month of each future time slice, for 4 demand regions. Time slices updated to align with latest WaterNSW approach.
Demand scaling method	Linear regression fitted through scatter plot of Sydney Water's demand factors for climate reference period vs future time slice to generate scaling factors	Same approach
Supply system yield estimation	Median, maximum, and range of impact of change in yield	Same approach

During the stakeholder consultation, Sydney Water stated its corporate position to prepare to adapt to a medium emissions pathway (SSP2-4.5 or equivalent) and demonstrate adaptive pathways to a high emissions scenario (SSP3-7.0, if available, or RCP8.5 if not) (Sydney Water, 2024c), with a preference to use the NARClIM projections (Sydney Water, 2024c). In discussions with Sydney Water, it was identified that Sydney Water also specifically requires an individual climate model projection corresponding to a high impact scenario under the SSP2-4.5 emissions pathway.

## 5.6 Review findings and recommendations

Based on the information provided for the review, our understanding of WaterNSW's current practices, and our knowledge of methods used to assess the impacts of climate change on system yield by other urban water service providers, researchers, and government agencies, HARC offers the following review findings and recommendations.

### 5.6.1 Historical climate change and hydroclimate data stationarity

The tests of climate and streamflow stationarity in WaterNSW's 2023 analysis relied upon visual inspection of time series and cumulative plots, plus averages or lines of best fit through the data. The assessment of the historical air temperature data stationarity in the climate change impact assessment methods report relied upon the R<sup>2</sup>-value as an indicator of the confidence level of the observed trend. It did not report on the level of statistical significance of the trend, which is a more common indicator of the ability to distinguish the trend from random variability in the data (e.g. a Mann-Kendall or similar test for trend).

The analysis of rainfall stationarity and inflow stationarity did not seek to isolate the effect of global warming on those hydroclimate variables. Co-variate analysis using annual-averaged daily maximum

air temperature as a co-variate (Kiem *et al.*, 2021) could be used to de-trend historical hydroclimate data for the effects of global warming on the instrumental hydroclimate record. That analysis (Kiem *et al.*, 2021) suggested that inflows in the Greater Sydney region have declined on average over many decades as global warming has increased, which could lead to an over-estimation of current yield when relying on the raw instrumental hydroclimate record. Similarly, PET is likely to have increased over time with global warming. The removal of the climate change signal, where it exists, aims to ensure that the historic hydroclimate record reflects behaviour that would be expected under current levels of global warming. The effects of historical bushfires on inflows are not expected to confound this analysis, because runoff recovery after fires in these mixed species forests is expected to be rapid, unlike the significant multi-decadal impact that can occur for other forest types. Air temperature data could be directly de-trended by fitting a linear regression through the data and then setting the slope of that regression to a horizontal line.

This identification of non-stationarity of the instrumental hydroclimate data and its de-trending would then allow an estimate of current yield to be generated that reflects the current level of global warming. Based on the analysis to date in the academic literature (Kiem *et al.*, 2021), current yield could be over-estimated without adjusting the instrumental hydroclimate datasets for historical global warming.

HARC recommendation	Level of effort	Likely impact on yield assessment
<p><b>#CC1: Historical climate change and hydroclimate data stationarity:</b> When considering the influence of climate change on hydroclimate observations, utilise formal statistical testing to identify any non-stationarity, and co-variate analysis using air temperature as a co-variate to de-trend rainfall and PET data for historical global warming. Air temperature data can be directly de-trended. Current yield should then reflect supply system behaviour at the current level of global warming.</p>	Medium	Medium

### 5.6.2 Rainfall-runoff model input rainfall

The Sacramento rainfall-runoff models of the dam catchments are used to calculate climate change factors for runoff. The calibration uses AWAP gridded climate data for the rainfall-runoff model calibrations because:

*“Climate models provides data in gridded format. Considering it, new rainfall-runoff models for catchments were calibrated using AWAP gridded rainfall datasets.” (WaterNSW, 2023).*

This suggests that the rationale for adopting the gridded climate datasets for rainfall-runoff model calibration was because NARClIM also uses gridded datasets. WaterNSW tested rainfall-runoff model performance using both at-site and gridded rainfall datasets, and concluded that both models predicted low flows well, but under-predicted high flows, and over-predicted recent low flows. Table 2 in the WaterNSW climate change impact assessment methods report (reproduced below as Table 5-3) indicates that the models using the gridded rainfall data over-predicted Warragamba inflows to a much greater extent than when using at-site rainfall data during the Tinderbox Drought of 2018 and 2019. This finding by WaterNSW is consistent with the MDBA’s *Hydrologic Modelling Practice Note* (MDBA, 2025), which recommends the use of gauged data (infilled and extrapolated over time as needed) in preference to gridded data, particularly in large catchments with low gauge density. Whilst the practice note includes the flexibility to use gridded data, it is preferentially reserved for cross-checking the spatial variability of climate data rather than for rainfall-runoff model calibration. The Victorian State

Government preferentially uses at-site data for rainfall-runoff model calibration, based on unpublished case study testing that indicated marginal calibration benefit from using gridded data, and the MDBA’s practice note. Gridded data based on interpolation between many gauges has the potential to increase the number of rain days, as well as smooth out rainfall peaks, relative to the use of at-site rainfall from one or relatively few nearby gauges.

Table 5-3 Estimation of annual inflows to Warragamba Dam in 2018 and 2019 low flow years (reproduced from Table 2 of (WaterNSW, 2023))

Year	Observed (GL/a)	Model based on Site Rainfall	Model based on Grid Rainfall
2018	106	118	169
2019	47	73	87

The illustration of gridded average annual rainfall over the Warragamba catchment (Figure 11) also suggests some spatial anomalies in the rainfall values in adjacent grid cells (i.e. grids with relatively high rainfall values immediately adjacent to grids with relatively low rainfall values).

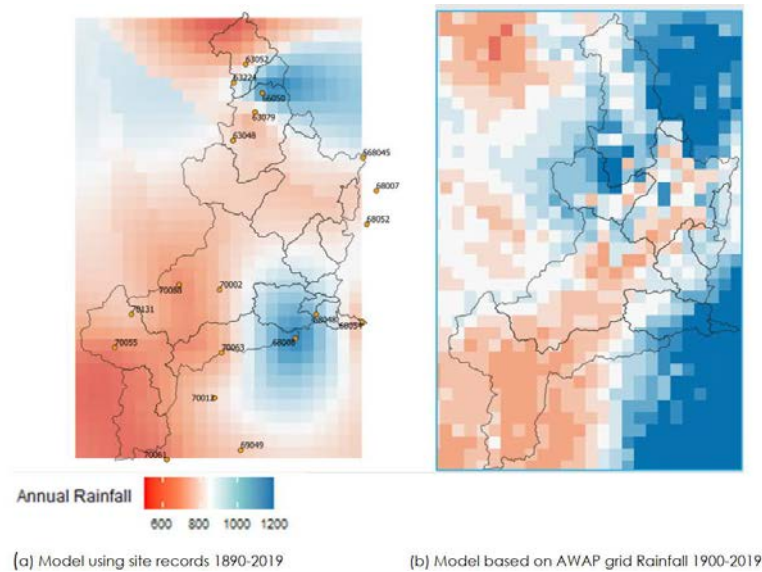


Figure 11 Warragamba rainfall-runoff model sub-catchments of mean annual rainfall using at-site and gridded rainfall (reproduced from Figure 13 in (WaterNSW, 2023))

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC2: Rainfall-runoff model input rainfall:</b> For the calibration of rainfall-runoff models used to calculate runoff change factors under climate change, the use of at-site rainfall data from one or relatively few nearby sites is preferred over the use of gridded rainfall products.	Low to Medium	Low

### 5.6.3 Rainfall-runoff model calibration accuracy

Hydrologic Simulation Program FORTRAN (HSPF) rainfall runoff models were previously used to reproduce historical inflows for all dams, but to date have only been used for yield assessments for the inflows to four of the dams. The HSPF models were originally calibrated with a primary focus of reproducing monthly flow duration curves and a secondary focus on low flow percentiles to inform environmental flows (SKM, 2011). Since around 2015, Sacramento rainfall-runoff models have replaced the HSPF models and have been developed with the aim of informing environmental flows (WaterNSW, 2026c). Previous reviews have recommended that the rainfall-runoff model calibration to assess yields should use objective functions specifically design with this in mind (SKM, 2011; WREMA and Kozarovski & Partners, 2016), with SKM (2011) identifying this task as a high priority.

WaterNSW recognises in its climate change impact assessment methods report that the rainfall-runoff models are not well calibrated to some parts of the flow regime and therefore their time series outputs are not suitable to directly use for climate change impact assessment. Instead, the models are used in a relative sense to estimate how the outputs from those models would change under different climate inputs, so that change factors can be generated and then subsequently applied to WaterNSW's higher quality inflow data. HARC agrees with WaterNSW's current position that the current rainfall-runoff models are not suitable to apply directly in climate change impact assessment and should only be used to calculate change factors to apply to other datasets. The rainfall-runoff model calibration performance would need to be improved (e.g. by the use of at-site rainfall data described above, the use of alternative calibration strategies, or alternative model structures) before their time series outputs could be used directly in the water resource modelling. The advantage of using the rainfall-runoff model outputs directly is that it captures any dynamic changes in daily rainfall infiltration, soil moisture storage and groundwater storage behaviour due to the impact of climate change on rainfall and PET. These can then cause changes in the timing and magnitude of individual runoff events. Such changes are not uniquely identified for individual runoff events when only using the rainfall-runoff model outputs to scale reference runoff datasets.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC3: Rainfall-runoff model calibration accuracy:</b> Retain current practice of only using rainfall-runoff models to calculate inflow change factors, rather than using time series outputs from those models directly in water resource modelling, until rainfall-runoff model calibration accuracy improves.	Low	None
<b>#CC4: Rainfall-runoff model calibration accuracy:</b> Re-run climate change yield assessment if improved rainfall-runoff model calibration can be achieved.	Medium	Medium

A further recommendation was made to seek to improve rainfall-runoff model calibration accuracy by exploring the use of at-site rainfall inputs, alternative model calibration strategies, or alternative model structures, with the aim to use the time series outputs from these models directly in water resources modelling if suitable calibration accuracy can be achieved. This recommendation is already reflected in recommendations H17 and H18 in Section 4.5.2.3.2 of this review.

### 5.6.4 Runoff in a drying climate

Non-stationarity of annual rainfall-runoff behaviour across south-east Australia following extreme drought was detected by the University of Melbourne and Monash University in some catchments

(DEECA, 2025a). That is, for the same annual rainfall, less runoff was being generated in the drought and post-drought period than in the pre-drought period. Non-stationarity of annual rainfall-runoff behaviour was also assessed in NSW in the northern Murray-Darling Basin, and whilst it indicated evidence of annual rainfall-runoff shift, the timing of this shift was different and was not attributable to extreme drought (Weligamage *et al.*, 2025). In Victoria the research led to the development of procedures that test for non-stationarity in the rainfall-runoff relationship and make adjustments to observed runoff prior to the Millennium Drought for consideration as part of sensitivity testing water security assessments (DEECA, 2025b). This is now available as an eWater community plug-in. Testing for changes in annual rainfall-runoff behaviour in the water supply catchments for Greater Sydney would need to be undertaken to inform whether this is likely to be an issue for these catchments or not.

In a drying climate under projected climate change, it is possible that catchments that have previously experienced a shift in rainfall-runoff behaviour during past droughts would be more likely to be in a lower runoff state than they have been historically. This behaviour can in theory be replicated by rainfall-runoff models, however the poor representation of long, slow dynamics within currently available rainfall-runoff models can hinder their ability to achieve this. In the approaches taken to date to address this issue in Victoria, having separate rainfall-runoff models that are well calibrated to pre-shift or post-shift datasets improves the ability to subsequently adjust input time series, if the shift is considered permanent. If the shift is considered temporary, then having a rainfall-runoff model that is well calibrated to both the pre- and post-shift periods is desirable and no adjustment for the shift would be needed. The likely permanence a shift in rainfall-runoff response can be informed by assessing the shift over different multi-year periods (as is undertaken in the plug-in mentioned above) or at a finer temporal scale by modelling the rainfall-runoff as single or multi-state processes, comparing the fit of single versus multi-state models and assessing the probability of shifts from states associated with drier conditions to states associated with wetter conditions (Peterson *et al.*, 2021b).

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC5: Runoff in a drying climate:</b> Report on the outcomes of investigating annual rainfall-runoff shift following severe drought in the Greater Sydney catchments. If a shift has been detected and has persisted post-drought, then adjust the pre-shift data to reflect the post-shift rainfall-runoff response and run as a sensitivity test of system performance for a drying climate change projection.	Medium	Low

### 5.6.5 Rainfall-runoff modelling in a world with higher carbon dioxide levels

Similar to almost all commonly used rainfall-runoff models, the Sacramento model is not capable of representing climate change impacts on vegetation water use arising from increasing CO<sub>2</sub> fertilization and temperature. Recent work (Rifai *et al.*, 2022) has shown widespread increases in Normalized Difference Vegetation Index (NDVI), a measure that indicates the health and density of vegetation, over much of eastern Australia. That work concluded that CO<sub>2</sub> fertilization has outpaced growing aridity to drive greening of Australian woody ecosystems, with a median increase in NDVI of 11.3 % across 90% of woody regions from 1982 to 2019. Higher atmospheric CO<sub>2</sub> concentrations generally increase plant water use efficiency, which may reduce plant transpiration per unit leaf area, but it can also lead to increased growth and therefore increased total plant transpiration (Fowler *et al.*, 2022). Denser vegetation also translates into greater rainfall interception. The use of rainfall-runoff models

that do not consider the influence of CO<sub>2</sub> fertilization are likely to over-estimate runoff under future higher levels of atmospheric CO<sub>2</sub>.

A recent trial application of a vegetation-aware rainfall-runoff model was commissioned by WaterNSW in two of Greater Sydney’s water supply catchments. It indicated improved rainfall-runoff model performance in split-sample testing during the Millennium Drought (very dry period) and after the Millennium Drought (wetter period) using a model that incorporated vapour pressure deficit, soil moisture, and the vegetation index EVI (Brieva *et al.*, 2025). Rates of evapotranspiration are expected to be different under higher air temperatures and higher concentrations of greenhouse gases in the atmosphere. Vegetation-aware rainfall-runoff models offer the possibility of improved rainfall-runoff modelling under alternative climate futures, provided that the additional model input variables can be estimated under projected climate change. As this is an area of research, it is recommended that WaterNSW maintain awareness of its development and provide support (e.g. with case studies or by providing supporting datasets) where there are opportunities to do so as part of broader industry collaboration.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC6: Rainfall-runoff modelling in a world with higher CO<sub>2</sub> levels:</b> Continue to support the development and testing of rainfall-runoff models by government that explicitly consider the effect of changes in climate on vegetation water use.	Medium	Low

### 5.6.6 Projection source and bias correction

WaterNSW has made use of the NARClIM climate change projections. The most recently available projections (1.5 or 2.0) have been used by WaterNSW as they have become available. HARC finds that the use of NARClIM1.5 datasets was fit-for-purpose at the time the climate change impact assessment methods report was written, and that WaterNSW’s current use of NARClIM2.0 is fit-for-purpose, given it is a NSW Treasury Common Planning Assumption and that it aligns with Sydney Water’s corporate position. For hydrologic modelling purposes, NARClIM2.0 supersedes NARClIM1.5 because of its higher performance for this purpose (DCCEEWS (NSW), 2024).

WaterNSW’s use of the bias-corrected outputs is considered by HARC to be preferred to using the raw NARClIM2.0 outputs. HARC recognises that bias-correction is undertaken by DCCEEWS’s NARClIM team as a whole-of-government process, and that any future updates to bias-correction techniques (e.g. any preferred techniques that emerge from the National Partnership for Climate Projections) would be undertaken by the NARClIM team, not WaterNSW. The bias correction method for NARClIM2.0 is the same as NARClIM1.5 and involves a quantile matching technique that corrects the rainfall and temperature data based on fitted distributions to daily model outputs to match AWAP 1990-2009 observations (DPIE, 2020). WaterNSW identified that even after bias-correction, there were still some residual biases in the NARClIM1.5 rainfall outputs, particularly when aggregating the climate model outputs over water supply catchment areas, and when considering multi-day rainfall events that may not have been the focus of the bias-correction. Whilst the NARClIM2.0 generated rainfall is known to have improved in accuracy relative to the NARClIM1.5 generated rainfall, some residual bias remains, which again reinforces the position to not utilise the NARClIM time series outputs directly in WaterNSW’s water resource modelling.

WaterNSW has used the raw PET projections from NARClIM and undertaken its own bias correction to those projections, because bias-corrected PET projections are not available from the NARClIM team. The process used and checks undertaken on this bias correction have not yet been written up and hence have not been reviewed by HARC. It is understood by HARC that the process involves bias-correcting to catchment average AWAP PET for catchment PET data, and bias-correction to the equivalent deep lake evaporation used in the CMCR calculations.

It is possible that the use of other regional climate models (i.e. not NARClIM) could generate different downscaled projections, however the risk of this is likely to be low if all NARClIM2.0 projections are utilised. There are other ways that may be more suitable for generating low likelihood, high impact climate change scenarios beyond those available from NARClIM2.0 (see Section 5.6.9).

The NARClIM2.0 rainfall projections are subject to high uncertainty from different climate models including both wetter and drier climate futures. In contrast, the NARClIM2.0 air temperature projections are confident in the direction of change, with much lower uncertainty in the magnitude of change. Co-variate analysis using air temperature as a co-variate is an alternative, data-driven approach for generating inflow projections, independent of the rainfall projections from climate models (Kiem *et al.*, 2021). This approach is still consistent with the Common Planning Assumptions, because it relies on the use of the NARClIM2.0 projections, but only for air temperature. It involves establishing a relationship between observed inflows and observed air temperature over recent decades, and then extrapolating that relationship to estimate projected future inflows over coming decades. Co-variate analysis is a useful, second line of evidence for climate change, and can help put the climate model projections in the context of observed hydroclimate change. Co-variate has the advantage that it avoids the uncertainties of climate (rainfall) modelling and rainfall-runoff modelling, and is a rapid assessment technique, relative to using climate model outputs. However it introduces its own uncertainties by using an annual temperature-runoff model. It assumes that the relationship between annual temperature and runoff is discernible from the noise in the data and is homogenous over the period of model fitting (typically confirmed using statistical tests such as split-sample tests), and that the relationship is robust across the range of observed inflows. It also assumes that the relationship will remain unchanged over future decades. As such, it will not identify any threshold changes in hydroclimate under future global warming that could be identified using climate models. For these reasons, it is not recommended as a sole line of evidence for climate change, but as a rapidly derived, data-driven, second line of evidence of climate change,

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC7: Projection source and bias correction:</b> Retain current practice of using bias-corrected NARClIM2.0 climate change projections. NARClIM1.5 projections are superseded. Document WaterNSW PET bias-correction methods, including checks that the bias correction preserves correlations between rainfall and PET.	Low	None
<b>#CC8: Projection source and bias correction:</b> Derive an inflow projection using co-variate analysis as a second line of evidence for climate change impact on yield, independent of rainfall modelling and rainfall-runoff modelling uncertainties.	Low	Low

### 5.6.7 Emission pathway selection

The use of climate model outputs from a range of plausible emission pathways is consistent with NSW Treasury requirements to consider climate change uncertainty as part of sensitivity test requirements for cost benefit analysis and business case submission (NSW Treasury, 2024a, 2024b, 2025).

The use of the NARClIM2.0 projections limits the choice of emissions pathway to SSP1-2.6, SSP2-4.5, and SSP3-7.0. Observed and likely future emissions and actions from the world's governments that affect future emissions are tracked and forecast by several organisations (CAT, 2025; IEA, 2025; UNEP, 2025). These generally indicate similar trajectories with a likely global warming level of 2-3°C above pre-industrial levels by the year 2100 (Hausfather, 2025). This trajectory is associated with a global warming level generated between those from emissions pathways SSP1-2.6 and SSP2-4.5, but closer to SSP2-4.5.

The higher emissions pathway SSP3-7.0 is a feasible but low likelihood pathway, whilst SSP5-8.5 is currently regarded as being of very low likelihood (Hausfather, 2025). Similarly, SSP1-1.9 would only eventuate if there were immediate, significant reductions in greenhouse gas emissions or sudden technological change to capture atmospheric carbon, which similarly makes it a highly unlikely emissions pathway. The use of SSP2-4.5 and SSP3-7.0, and the previous use of RCP4.5 and RCP8.5, align with Sydney Water's corporate position.

HARC agrees with WaterNSW that the use of SSP1-2.6 is a lower priority for yield analysis because it is not information needed by Sydney Water. However, based on the analysis of emissions trajectories described above, SSP1-2.6 is currently a higher likelihood scenario than SSP3-7.0, and yield estimates under this scenario remain valuable for considering the robustness of future supply system configuration and operation to this plausible, albeit lower likelihood, climate future.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC9: Emission pathway selection:</b> Retain the current practice of preparing climate change factors for all NARClIM2.0 emission pathways, so that they are available to use in sensitivity analyses.	Low	None

### 5.6.8 Climate model selection

The use of climate model outputs from a range of different climate models is consistent with NSW Treasury requirements to consider climate change uncertainty as part of sensitivity test requirements for cost benefit analysis and business case submission (NSW Treasury, 2024a, 2024b, 2025). Sydney Water also specifically requires an individual climate model projection corresponding to a high impact climate model run under the SSP2-4.5 emissions pathway.

WaterNSW undertakes some of its analyses using ensemble mean projections, but also reported on the range of impacts on yield from the full ensemble in its 2023 analysis. In the context of both wetter and drier climate futures for Greater Sydney, an ensemble mean is likely to be less informative than different climate storylines generated from individual climate model projections. The use of 3-4 storylines is suggested by HARC, identified using maximum reservoir drawdown under an instrumental climate sequence as a proxy for system performance. At least one of the storylines would correspond to Sydney Water's information needs (i.e. the climate model outputs that generate

maximum reservoir drawdown under SSP2-4.5), with two storylines representing upper and lower bounds of maximum reservoir drawdown when applying all of the NARClIM2.0 projections.

The NARClIM2.0 global climate models were pre-selected by DCCEE from the Intergovernmental Panel on Climate Change’s latest CMIP6 climate model ensemble as those which were independent, well-performing models over Australia (Di Virgilio *et al.*, 2022, 2025). The global climate models adopted for use in the NARClIM2.0 regional climate modelling were demonstrated to capture the range of mean precipitation change in south-east Australia from the CMIP6 global climate models (Di Virgilio *et al.*, 2022, 2025). The range of mean temperature change is mostly well captured, with only one global climate model generating a projected temperature change outside of the NARClIM2.0 model output range. This means that utilising additional climate model outputs from other climate modelling exercises, in additional NARClIM2.0, would most likely be of limited value.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC10: Climate model selection:</b> Retain the current practice of preparing climate change factors for all NARClIM2.0 global/regional climate model combinations, so that they are available to use in sensitivity analyses.	Low	None
<b>#CC11: Climate model selection:</b> For reporting purposes, report on at least the highest impact climate scenario under SSP2-4.5, and the range of impacts from all NARClIM2.0 runs.	Low	None

### 5.6.9 Climate model output checks

A range of climate model output checks were made by WaterNSW to confirm the effectiveness of the bias correction, and to identify any residual rainfall bias in the model outputs across WaterNSW’s water supply catchments. These checks were an appropriate way to understand the spatial variability of the NARClIM1.5 outputs and to justify the use of climate change scaling factors rather than the direct use of climate model outputs (raw or bias-corrected) in the water resource modelling.

The comparisons between the NARClIM outputs and AWAP gridded rainfall are influenced by any bias in the AWAP rainfall grids. A truer indication of climate model bias in rainfall would be obtained by comparing the climate model outputs with at-site data at a rainfall gauge for say 2-3 representative locations with suitable observed rainfall data. Checks over different historical time periods would also provide any insights into the effectiveness of the bias correction in wet and dry years, and wet and dry decades.

Some of the checks undertaken in the 2023 assessment are not interpreted in the accompanying text, and either alternative checks that are more meaningful to WaterNSW could instead be undertaken, or the text could be updated to interpret the outputs from the checks more clearly. For example, the section on “droughts in future climate simulations” presents cumulative annual rainfall deviation plots of each of the climate models versus AWAP data. The presence or absence of similar-to-historic droughts is not immediately obvious in these plots, and perhaps statistics of minimum cumulative annual rainfall totals over single and multi-year periods could better inform the interpretation of drought behaviour in the climate models. The examination of annual serial correlation of rainfall by WaterNSW is informative for understanding the potential of observed rainfall persistence in many of the climate model outputs.

The conclusion drawn by WaterNSW from the projected changes in rainfall events is that there are no significant changes in the number of rainfall events in the near and far future climate simulations, however some of the data is significantly different (e.g. 3-5 day rainfall event frequency for model KESM2 is twice as high in the far future period than the near future period).

When updating the climate change analysis in 2026 using NARClIM2.0 data, the labelling of some tables and charts could be updated to improve clarity for readers.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC12: Climate model output checks:</b> Undertake checks of climate model outputs at a selection of gauged rainfall locations to ensure key characteristics are reproduced, in addition to the current more general checks against gridded observed rainfall datasets.	Low	None
<b>#CC13: Climate model output checks:</b> Revisit the climate model output checks to generate meaningful interpretation of those checks, which may involve changing the type of checks being presented to enable greater meaning to be drawn from them.	Low	None
<b>#CC14: Climate model output checks:</b> Ensure all figures and tables include clear descriptions of variables, their units, and reference periods (where applicable) on axis labels and titles.	Low	None

## 5.6.10 Climate change scaling factors

### 5.6.10.1 Climate reference periods and time slice duration

WaterNSW's climate change scaling uses a time slice method (discussed further in Section 5.6.10.2), where WATHNET model inputs are scaled based on the average values of the hydroclimate variable in a future time slice relative to a reference time slice. WaterNSW has modified its time slice duration from 40-years to 30-years to align with the 30-year duration time slice adopted by NSW DCCEEW in its *Framework for Selecting and Preparing Climate Change Data for Hydrological Modelling Purposes*. These time slices are 10 years longer than the time slices used in the AdaptNSW interactive map of NARClIM2.0 projections, as shown in Table 5-4.

Table 5-4 Comparison of reference periods in different applications

Historical time slice period (and duration in years)	Future time slice duration (years)	Reference
1980-2019 (40 years)	40	WaterNSW yield assessment (WaterNSW, 2023)
1996-2025 (30 years)	30	WaterNSW's 2026 approach
1976-2005 (30 years)	30	DCCEEW Regional Water Strategies, (DCCEEW (NSW), 2026a), (DPE, 2022)
1990-2009 (20 years)	20	AdaptNSW Interactive Climate Change Projections Map (NSW Government, 2025)

WaterNSW's choice of a 40-year time slice in the 2023 climate change impact analysis work is in HARC's opinion likely to be more suitable for hydrologic applications than adopting a 20-30 year time slice. This is because the longer time slice is able to more effectively smooth out the climate variance embedded within the climate model outputs. This is illustrated by HARC using a sample NARClIM2.0 grid cell output (in the Warragamba Dam catchment) to generate average annual rainfall change using

either 30-year time slices or 40-year time slices (Figure 12). In this example the change is expressed relative to 1990, simply because that was what aligned with the DCCEE framework. It can be seen in this figure that the variance in the calculated change in average annual rainfall from year to year is much higher when using a 30-year time slice and that the amplitude of the change, as indicated by the range of outcomes relative to a line of best fit through the data, is also much higher.

The magnitude of the change is also sensitive to the duration of the time slice (i.e. consistently lower with the 40-year time slice), but it is unclear whether the lower magnitude is an artefact of this particular dataset, or whether it would apply more generally to other datasets.

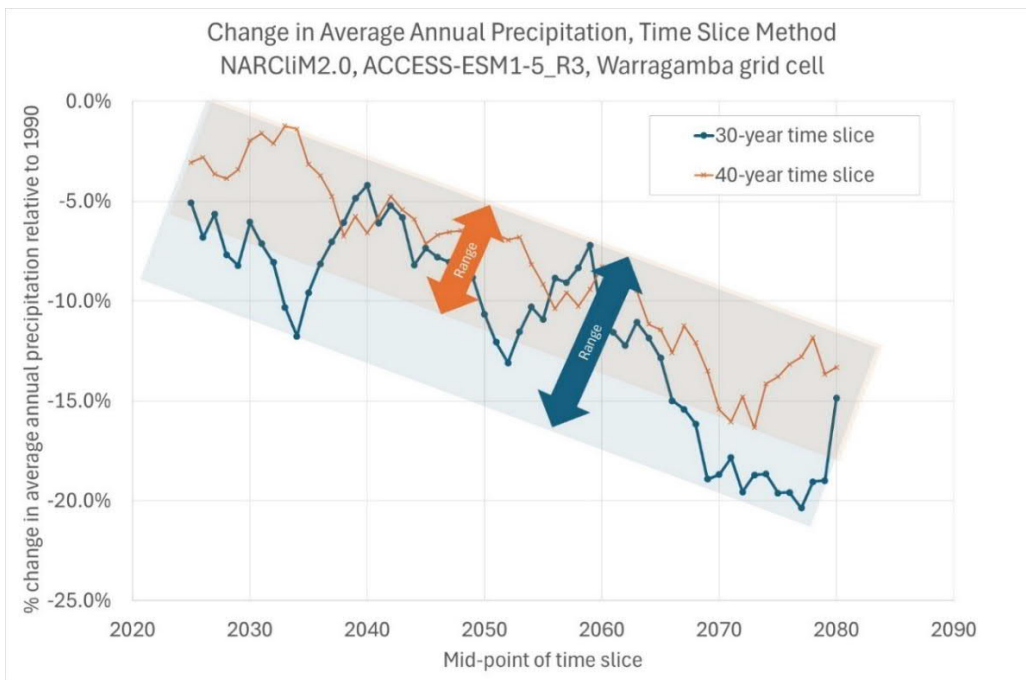


Figure 12 Stability of average annual rainfall change projections using 30-year or 40-year time slices

It is however recognised by HARC that there are benefits in aligning assessment processes across different applications in the same region by WaterNSW and DCCEE, and for this reason, a 30-year time slice is appropriate, until the climate change working group has completed the proposed testing of time slices of different lengths on a broader range of climate variables, locations, and climate models than the single example presented by HARC above. However, if cross-agency alignment was the objective for adopting a 30-year time slice, then this objective is not achieved by WaterNSW when adopting a 1996-2025 climate reference period, rather than DCCEE's 1976-2005 climate reference period. This means that WaterNSW will be reporting climate change impacts relative to 2010, but DCCEE will be reporting climate change impacts relative to 1990, which has the potential to create confusion amongst stakeholders and limit their ability to compare climate change impacts on water resources for different applications in the Greater Sydney area, and between Greater Sydney and other regions.

The choice of a 1976-2005 vs 1996-2025 climate reference period will be influenced by the stationarity of data over these two periods, and the extent to which those reference periods are representative of the statistical characteristics of the instrumental climate reference period used to define climate variability (from the late 19<sup>th</sup> or early 20<sup>th</sup> century to date). DCCEE stated that the 1976-2005 period matches characteristics of the longer instrumental rainfall record (1890-2019) that is used by DCCEE for paleo-stochastic data generation. Other reasons included its data length to capture

climate variability and the spatial coverage of available observations across NSW. It was adopted in the Fish River Wywandy Regional Water Strategy, and aligns with the MDBA’s climate change projections from a 1990 baseline for the Basin Plan Review (DCCEEW (NSW), 2026a). Adopting a more recent climate reference period (i.e. 1996-2025) would narrow the climate change projections but requires that any non-stationarity in the instrumental climate record leading up to 2010 (i.e. the mid-point of the 1996-2025 period) is accounted for. Whichever reference period is selected when using the time slice method, the mid-point of that reference period would be considered the point in time from which change factors are generated. The results of testing of WaterNSW’s alternative climate reference period would benefit from discussion with the metropolitan climate change working group.

For the future time slices, WaterNSW has adopted a near-future time slice centred on 2055 and a far future time slice centred on 2085. The year 2055 corresponds to the anticipated end of the assessment period for the next Long-Term Capital and Operational Plan, as conveyed to WaterNSW by Sydney Water (A. Breda, WaterNSW, pers. comm. to HARC 12/3/26). A 40-year planning horizon would be suitable for most applications, with a notional 10-year allowance for any lag between data processing and its use in planning activities. The end of such a planning horizon would be around 2065-2080. Whilst the use of scaling factors that apply directly to the end of the planning horizon would be ideal, without knowing precisely when that will be for future applications, using a time slice centred on 2085 will allow interpolation of yield estimates back to the period 2065-2080 with likely negligible loss in accuracy.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC15: Climate change scaling factors:</b> When using the time slice method to calculate change factors, investigate the effect of adopting either a 30-year or 40-year time slice, collaboratively with the metropolitan climate change working group (DCCEEW, WaterNSW, Sydney Water, Hunter Water).	None	None
<b>#CC16: Climate change scaling factors:</b> When using the time slice method to calculate change factors, align the climate reference period with guidance from DCCEEW and the Metropolitan Climate Change Working Group (currently 1976-2005). Share and discuss the results of testing of WaterNSW’s alternative climate reference period with the group.	Low (if changed quickly)	Low

### 5.6.10.2 Scaling method

A time slice method has been adopted by DCCEEW for its Regional Water Strategies, is embedded in DCCEEW’s *Framework for selecting and preparing climate change data for hydrological modelling purposes* and to date has been the most widely used technique for scaling historical data for future climate change for hydrological applications. As such it reflects a commonly adopted contemporary practice.

Recently, CSIRO has applied a different scaling technique known as pattern scaling. This has been applied when developing the hydroclimate projections for the MDBA’s *Basin Plan Review* and for some of the Victorian State Government’s climate change guidance (Chiew *et al.*, 2025; DEECA, 2025b). It involves fitting a relationship between mean modelled global temperature anomaly (from the

IPCC CMIP6 ensemble<sup>3</sup>) and the climate variable of interest (from local climate projections, e.g. NARCIIM2.0). It has previously been applied on both annual and seasonal time steps. The aim of this technique is to remove the noise in the climate model outputs due to climate variability, to detect the underlying climate change signal.

An example relationship is shown in Figure 13, which in this case indicates an underlying linear trend of a 90 mm/year reduction in annual rainfall for every degree of global warming. This example is for a location in the Warragamba catchment, using the NARCIIM2.0 outputs for one GCM/RCM projection for the SSP2-4.5 emissions scenario.

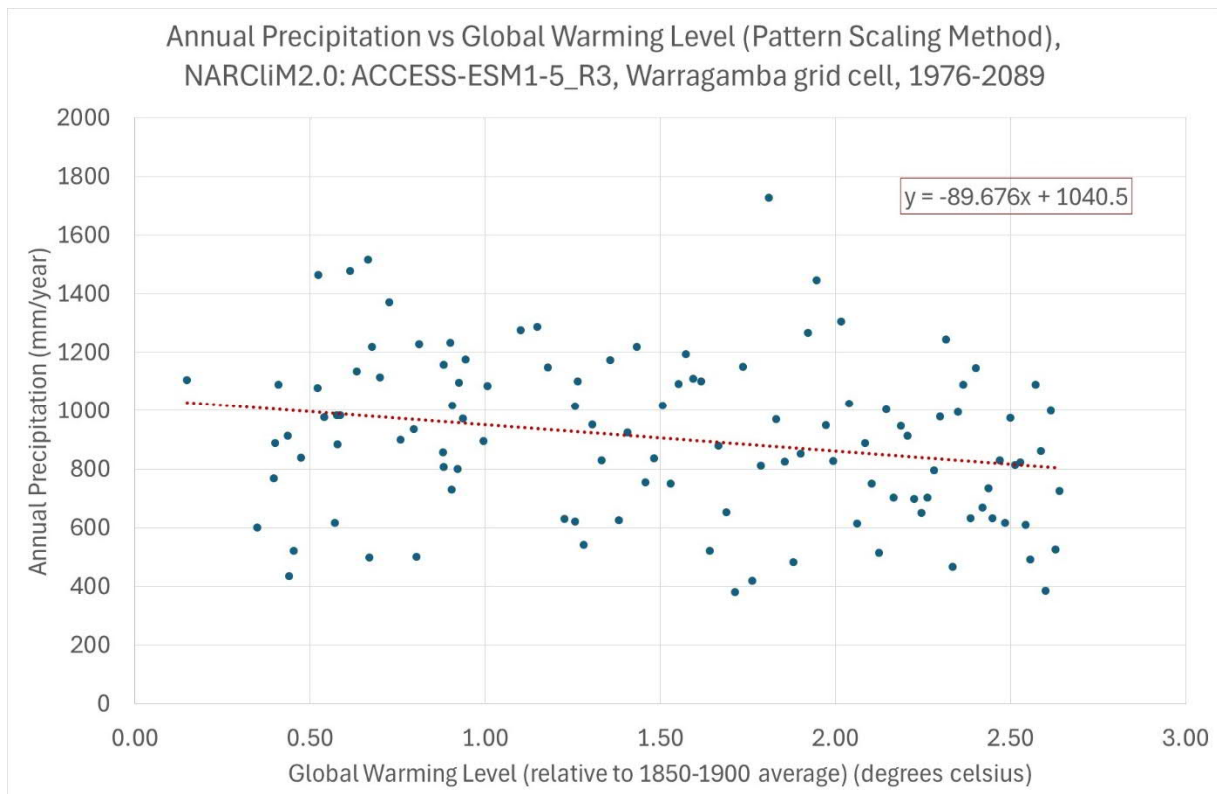


Figure 13 Illustrative example of a relationship between global warming level and climate model annual precipitation, 1976-2089, for a sample NARCIIM2.0 output grid cell, model, and emissions pathway

This relationship can then be used to estimate the projected incremental change in annual rainfall for any incremental change in global warming, which can then readily be converted to a non-linear relationship between projected change in annual rainfall and time, as shown in Figure 14. This figure demonstrates how the pattern scaling approach effectively puts an approximate line of best fit through the time slice method estimates each year to reveal the underlying climate change signal.

Local testing of the pattern scaling approach is required to confirm its suitability across WaterNSW's supply catchments, the period of assessment to adopt to avoid any adverse end effects on the linear regression through the planning horizon, and the suitability of the method for all SSPs. This is particularly for SSP1-2.6 where there is the possibility of non-linear relationships between incremental global temperature change and rainfall change during global warming, stabilisation, and global cooling

<sup>3</sup> <https://catalogue.ceda.ac.uk/uuid/98af2184e13e4b91893ab72f301790db/>

phases. This testing could include testing the statistical significance of relationships and consideration of whether to adopt particular levels of significance to determine whether a projected change differs from no change given the noise in the projections. Note that this aspect (testing for statistical significance) was not mentioned in the report published by CSIRO for the MDB climate change projections using pattern scaling (Chiew *et al.*, 2025) and is also not typically undertaken when applying the time slice method.

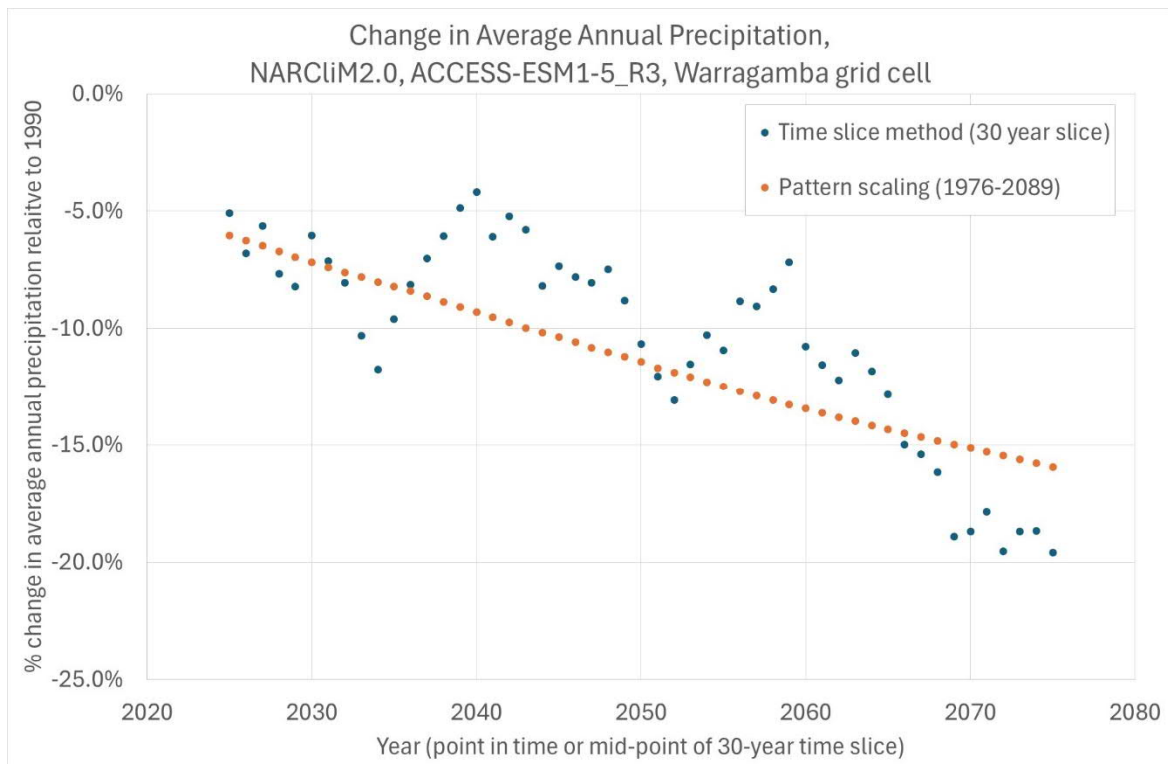


Figure 14 Comparison between time slice method and pattern scaling method for change in average annual precipitation relative to the year 1990 for an example location and climate projection

Pattern scaling is similar to the historical co-variate analysis described previously in Section 5.6.6, but (i) the source of data is different, coming from the climate model projections rather than historical observations, and (ii) it is typically applied to parameter characteristics beyond just the mean annual change (although the same could also be done for the historical co-variate analysis). The key advantage of pattern scaling over historical co-variate analysis is that it can identify future changes in the relationship between global warming and the climate parameters of interest, and non-linear runoff responses to those changes, rather than assuming the historical relationship will continue to hold over the planning horizon. As discussed previously, the use of climate model outputs (in pattern scaling or the time slice method) introduces climate model and rainfall-runoff model uncertainties when estimating projected changes in inflows under climate change that do not affect historical co-variate analysis.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC17: Climate change scaling factors:</b> Support local testing of the pattern scaling approach by the Metropolitan Climate Change Working Group and, together with other stakeholders, transition to its use for	High	High

climate change projections, if it is found to be more fit-for-purpose locally than the time slice method in reducing the signal-to-noise ratio from the climate change projections.

### 5.6.10.3 Parameter characteristics to scale

The use of a linear relationship between historic and future climate model outputs means that different scaling factors can be applied depending on whether the values are higher or lower. This process has a similar effect to quantile-quantile scaling (where individual percentile values are scaled uniquely), but with some additional smoothing of the relationship across percentile values to avoid anomalous scaling factors. The different scaling of rainfall on days of very heavy rainfall is supported by *Australian Rainfall and Runoff's* climate change considerations because it is behaviour that has been observed over recent decades. In the absence of similar evidence for other (lower magnitude) rainfall events, it is difficult to justify the different factoring of other rainfall events. The use of scaling techniques that utilise mean monthly scaling for rainfall and mean seasonal scaling (cool/warm season) for PET and air temperature, with additional scaling of days of very heavy rainfall (exceeded, on average, no more frequently than once per year) can simplify the scaling process. When scaling days of very heavy rainfall, an adjustment is made to the scaling of rainfall on other days so as to preserve the mean rainfall projections.

It is possible that by fitting a single linear regression through all exceedance percentiles, any unique behaviour on days of very heavy rainfall could be missed. WaterNSW did not report an example of its rainfall scaling in its 2023 report, so HARC has relied upon the inflow scaling example in Figure 15 to illustrate this. In this figure, it can be seen that the slope of the relationship between the historic and the projected future inflow is generally the same, implying reasonably consistent behaviour that could reasonably be characterised by the mean inflow change across most of the data. However, the far future winter inflow change shows quite different behaviour in the very high flow range (indicated by the data points in the green circle), which could be driven by a different rainfall change (or its associated runoff response) on days of very high rainfall. Separately calculating rainfall change on days of very high rainfall, and very high inflows if scaling inflows directly, could capture this behaviour more effectively.

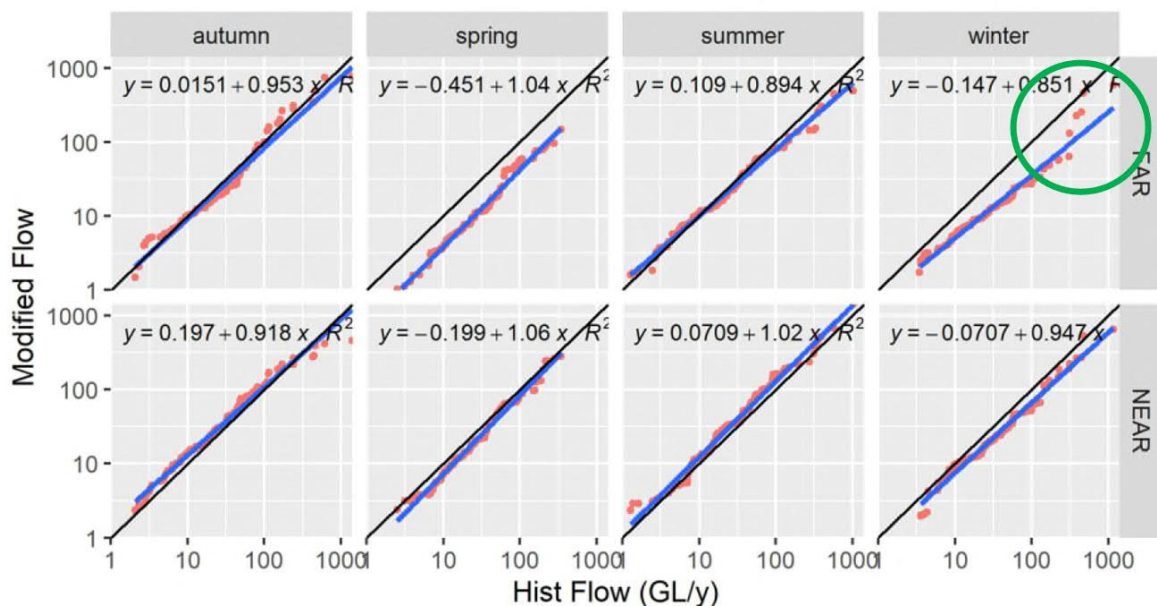


Figure 15 Linear regression (blue line) fitted to historical and climate change projected inflows (red dots) for an example climate model and inflow location (WaterNSW, 2023), green circle added by HARC.

Both time slice and pattern scaling approaches can be applied seasonally, and to specific parameter characteristics (e.g. different scaling factors for different exceedance percentiles). However, these scaling approaches do not change the climate sequencing as a result of global warming. The sequencing from the stochastic inflow sequences under baseline conditions is largely retained, apart from changes in flow associated with different change factors applied to different seasons or different parts of the flow regime. The running of climate models stochastically for CMIP7 (Funke *et al.*, 2024) may directly address this sequencing issue in the future.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC18: Climate change scaling factors:</b> Simplify the climate change scaling where more detailed scaling is not supported by historical evidence of change under global warming to date or a clear and defensible conceptual model of why the change would occur.	Low	Low
<b>#CC19: Climate change scaling factors:</b> Separately scale rainfall on days of very heavy rainfall (and associated inflows if scaling inflows directly) to separately account for changes in rainfall intensity to these high intensity rainfall events.	Medium	Low

### 5.6.11 Climate change impact on demands

The meta-information provided by Sydney Water to WaterNSW includes a covering email, as well as a metadata within the spreadsheet that contains the demand disaggregation factors under projected climate change. This metadata includes the climate projection data source, emissions pathway, time slice durations, the type of residential demand model used, and population/dwelling assumptions. However, there is no consolidated documentation from Sydney Water that WaterNSW can reference about the demand modelling, the adjustments of those demands under projected climate change, and any quality control checks that Sydney Water has undertaken before providing the demand disaggregation factors to WaterNSW. The documentation could include, for example, how Sydney Water has undertaken its rainfall, temperature and evaporation factoring under projected climate change, so that WaterNSW can confirm that both organisations are using the same analysis techniques (or have different techniques for transparent reasons specific to the different applications), as well as confirmation that the demand model is generating reasonable values when using climate inputs that fall outside of the range over which the demand models were calibrated. This documentation would also assist with future independent reviews.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC20: Climate change impact on demands:</b> WaterNSW request that Sydney Water provide consolidated documentation to WaterNSW about its demand modelling methods and assumptions under projected climate change and any associated quality control checks on the calculated climate change scaling factors	Low	None

### 5.6.12 Low likelihood, high impact climate change scenarios

The climate change impact assessment undertaken by WaterNSW currently relies solely upon the NARCIIM2.0 climate projections. These projections include outputs for a range of emissions pathways and climate models, presented as a range of potential climate futures. Whilst NARCIIM2.0 provides the current best representation of modelled climate change projections for the Greater Sydney region, there is nevertheless a possibility that future climate conditions could lie outside of the range of modelled projections, albeit with low likelihood. This could occur, for example, if climate model or emissions pathway assumptions end up being incorrect, as could occur due to say unmodelled carbon cycle feedback loops, reaching unmodelled global climate tipping points, higher than anticipated greenhouse gas emissions from individual nations, or uncertainties in vegetation behaviour and hence runoff under higher levels of atmospheric carbon dioxide. Indirect climate change pathways that fall outside of WaterNSW's current WATHNET modelling processes could also threaten supply system yield, such as increased bushfire risk, increased algal bloom risk, and increased risk of severe storms or hail events under projected climate change. Climate related hazards can affect part or all of the supply system, and the severity of these impacts can sometimes be quite localised. The previous damage to the Sydney desalination plant as a result of a severe storm event is a practical example of how climate related hazards can affect supply system yield, with the likelihood of many of those hazards increasing under projected climate change. For these reasons, the MDBA's Independent Hydroclimate Expert Panel recommended that low likelihood, high impact climate change scenarios generated independently from the traditional modelling should be considered in water resource planning (IHSEP, 2025; John *et al.*, 2026).

Devising plausible and meaningful low likelihood, high impact climate change scenarios that do not come directly from climate model projections can be challenging. One option is to undertake supply system shock testing that assesses the impact of a loss of critical water harvesting sources or distribution assets for an extended period. This would be an indicator of potential risks under low likelihood, high impact climate change scenarios that may fall outside of the impacts projected by NARCIIM2.0. Such an approach allows system resilience to be assessed in the event of natural hazards whose likelihood may be increased under future climate conditions. System shocks would need to be derived collaboratively by supply system operators and planners but could include an extended outage of the Sydney Desalination Plant, or disruption to the supply from particular storages.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC21: Low likelihood, high impact climate change scenarios:</b> WaterNSW consider the possibility of one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs.	Medium	High

### 5.6.13 Managing expectations of climate change certainty over time

Climate change science continues to progress, climate change projections are periodically updated, policies from the world's governments influencing emissions trajectories sometimes change, and climate change impact assessment methods continue to evolve. In this context, it is unreasonable to expect that a yield estimate under climate change will remain the same from one assessment to the next. This contrasts with a natural desire for certainty in yield estimates under projected climate change by decision-makers and stakeholders. To assist in managing expectations about certainty in climate change projections from one assessment to the next, documenting the reasons for change

(e.g. using the next generation NARClIM2.0 climate model projections instead of NARClIM1.5, using CMIP6 projections instead of CMIP5, etc.) will help to educate end users of the yield estimates that although they are based on the best available science and assessment methods at the current time, they may change in the future.

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC22: Managing expectations of climate change certainty over time:</b> WaterNSW document the main reasons for changes in yield estimates under projected climate change in the 2026 assessment, relative to the 2023 assessment.	Low	None

## 5.7 Conclusions and recommendations for climate change assessments

Based on the information provided for the review, our understanding of WaterNSW’s current practices, and our knowledge of methods used to assess the impacts of climate change on system yield by other urban water service providers, researchers, and government agencies, HARC concludes that:

- The climate change impact assessment undertaken in 2023 for the Long-Term Capital and Operational Plan was fit-for-purpose, reflecting contemporary good practice at the time of that assessment. The assessment included WaterNSW documentation on methods, assumptions, their justification, and quality control/assurance checks.
- It is difficult for HARC to fully assess the suitability of WaterNSW’s 2026 climate change impact assessment methods and assumptions, because those methods are currently being developed and applied, and have not yet been documented. The review recommendations provided by HARC on the 2026 methods offer an opportunity for WaterNSW to consider and adapt its methods as they are implemented.

Following our review, HARC offers the following over-arching recommendations for WaterNSW:

- **To continue to test recent innovations in climate change impact assessment methods with the aim of transitioning to improved methods** where they are demonstrated to provide benefits locally. These include (i) co-variate analysis to investigate and potentially address any effects of historical climate change on data stationarity and to provide a second line of evidence of projected climate change independent of climate model rainfall projections, and (ii) pattern scaling to reduce the signal to noise ratio in climate model outputs and to better support any future transient-state water resource modelling.
- **To continue to collaborate with other agencies to achieve consistency in climate change assumptions** across NSW Government stakeholders where it is reasonable to do so, particularly through ongoing participation in DCCEE’s metropolitan climate change working group, continued alignment with NSW Treasury’s Common Planning Assumptions for climate change, and continued sharing of climate change impact assessment assumptions and methods with Sydney Water and other stakeholders.
- **To continue to analyse and provide guidance on the full range of yield estimates** from all NARClIM2.0 projections, rather than focussing on only a single climate future. This is important for supporting assessments of supply system robustness to future climate uncertainty.

Given the importance of rainfall-runoff models for estimating climate change factors for inflows to the water supply system, it is also recommended that rainfall-runoff model calibrations are revisited, as per the previously stated over-arching recommendation.

A small number of these recommendations (#1, #4, #17) could materially impact the estimate of yield under projected climate change and should be addressed as a matter of priority, however all of these recommendations are not low effort and may take some time (likely to take many months, not days or weeks) to test and confirm their suitability prior to adoption. The remainder will improve the clarity and defensibility of WaterNSW’s hydrologic methods. Of the recommendations classified as being of relatively low effort, the most material of these are recommendations #11, which will meet an immediate stakeholder need, and #16 to align some assumptions with DCCEEW, which will make communication and comparability of climate change impacts across applications in the Greater Sydney region much easier. Recommendation #16 could become a medium to high effort task if not completed quickly, because all subsequent analysis relies upon this initial assumption.

Addressing these requirements will ensure that WaterNSW unambiguously addresses the WaterNSW Operating Licence 2024-2028 obligations regarding reporting, record keeping, and ease in providing information. Addressing the recommendations will help WaterNSW to maintain contemporary good practice in this field. Improved documentation will improve transparency in the modelling process, which should increase both WaterNSW and stakeholder confidence in the model results.

Table 5-5 List of specific recommendations from climate change impact assessment review

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC1: Historical climate change and hydroclimate data stationarity:</b> When considering the influence of climate change on hydroclimate observations, utilise formal statistical testing to identify any non-stationarity, and co-variate analysis using air temperature as a co-variate to de-trend rainfall and PET data for historical global warming. Air temperature data can be directly de-trended. Current yield should then reflect supply system behaviour at the current level of global warming.	Medium	Medium
<b>#CC2: Rainfall-runoff model input rainfall:</b> For the calibration of rainfall-runoff models used to calculate runoff change factors under climate change, the use of at-site rainfall data from one or relatively few nearby sites is preferred over the use of gridded rainfall products.	Low to Medium	Low
<b>#CC3: Rainfall-runoff model calibration accuracy:</b> Retain current practice of only using rainfall-runoff models to calculate inflow change factors, rather than using time series outputs from those models directly in water resource modelling, until rainfall-runoff model calibration accuracy improves.	Low	None
<b>#CC4: Rainfall-runoff model calibration accuracy:</b> Re-run climate change yield assessment if improved rainfall-runoff model calibration can be achieved.	Medium	Medium
<b>#CC5: Runoff in a drying climate:</b> Report on the outcomes of investigating annual rainfall-runoff shift following severe drought in the Greater Sydney catchments. If a shift has been detected and has persisted post-drought, then adjust the pre-shift data to reflect the post-shift rainfall-runoff response and run as a sensitivity test of system performance for a drying climate change projection.	Medium	Low
<b>#CC6: Rainfall-runoff modelling in a world with higher CO<sub>2</sub> levels:</b> Continue to support the development and testing of rainfall-runoff models by government that explicitly consider the effect of changes in climate on vegetation water use.	Medium	Low

HARC recommendation	Level of effort	Likely impact on yield assessment
<b>#CC7: Projection source and bias correction:</b> Retain current practice of using bias-corrected NARClIM2.0 climate change projections. NARClIM1.5 projections are superseded. Document WaterNSW PET bias-correction methods, including checks that the bias correction preserves correlations between rainfall and PET..	Low	None
<b>#CC8: Projection source and bias correction:</b> Derive an inflow projection using co-variate analysis as a second line of evidence for climate change on yield, independent of rainfall modelling and rainfall-runoff modelling uncertainties.	Low	Low
<b>#CC9: Emission pathway selection:</b> Retain the current practice of preparing climate change factors for all NARClIM2.0 emission pathways, so that they are available to use in sensitivity analyses.	Low	None
<b>#CC10: Climate model selection:</b> Retain the current practice of preparing climate change factors for all NARClIM2.0 global/regional climate model combinations, so that they are available to use in sensitivity analyses.	Low	None
<b>#CC11: Climate model selection:</b> For reporting purposes, report on at least the highest impact climate scenario under SSP2-4.5, and the range of impacts from all NARClIM2.0 runs.	Low	N/a
<b>#CC12: Climate model output checks:</b> Undertake checks of climate model outputs at a selection of gauged rainfall locations to ensure key characteristics are reproduced, in addition to the current more general checks against gridded observed rainfall datasets.	Low	None
<b>#CC13: Climate model output checks:</b> Revisit the climate model output checks to generate meaningful interpretation of those checks, which may involve changing the type of checks being presented to enable greater meaning to be drawn from them.	Low	None
<b>#CC14: Climate model output checks:</b> Ensure all figures and tables include clear descriptions of variables, their units, and reference periods (where applicable) on axis labels and titles.	Low	None
<b>#CC15: Climate change scaling factors:</b> When using the time slice method to calculate change factors, investigate the effect of adopting either a 30-year or 40-year time slice, collaboratively with the metropolitan climate change working group (DCCEEW, WaterNSW, Sydney Water, Hunter Water).	None	None
<b>#CC16: Climate change scaling factors:</b> When using the time slice method to calculate change factors, align the climate reference period with guidance from DCCEEW and the Metropolitan Climate Change Working Group (currently 1976-2005).	Low (if changed quickly)	Low
<b>#CC17: Climate change scaling factors:</b> Support local testing of the pattern scaling approach by the Metropolitan Climate Change Working Group and, together with other stakeholders, transition to its use for climate change projections, if it is found to be more fit-for-purpose locally than the time slice method in reducing the signal-to-noise ratio from the climate change projections.	High	High
<b>#CC18: Climate change scaling factors:</b> Simplify the climate change scaling where more detailed scaling is not supported by either historical evidence of change under global warming to date or a clear and defensible conceptual model of why the change would occur.	Low	Low
<b>#CC19: Climate change scaling factors:</b> Separately scale rainfall on days of very heavy rainfall (and associated inflows if scaling inflows directly) to separately account for changes in rainfall intensity to these high intensity rainfall events.	Medium	Low
<b>#CC20: Climate change impact on demands:</b> WaterNSW request that Sydney Water provide consolidated documentation to WaterNSW about its demand modelling methods and assumptions under projected	Low	None

HARC recommendation	Level of effort	Likely impact on yield assessment
climate change and any associated quality control checks on the calculated climate change scaling factors		
<b>#CC21: Low likelihood, high impact climate change scenarios:</b> WaterNSW consider the possibility of one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs.	Medium	High
<b>#CC22: Managing expectations of climate change certainty over time:</b> WaterNSW document the main reasons for changes in yield estimates under projected climate change in the 2026 assessment, relative to the 2023 assessment.	Low	None

## 6. Review of the WATHNET Model and yield calculation approach

The WATHNET model and the yield modelling approach was reviewed, paying particular attention (but not limited to) changes made to the model since the 2021 review, implementation of recommendations from the 2021 Model Review (WREMA, 2021) and implementation of recommendations from the 2025 Interim Review (Kuczera, 2025) including those related to model settings, model configuration and scripting and/or the suitability of the recommendations considering the investigations undertaken by WaterNSW.

### 6.1 WATHNET model review

The WATHNET model review was undertaken by examining each element of the model, taking into consideration changes made since the last review (Section 6.1.2) and implementation of recommendations arising from the 2021 and 2025 reviews (Section 6.1.1).

The review encompasses model elements such as:

- The physical system – representation, constraints, layout, extent, discretisation
- Model inputs – demands and how inflow and climate inputs are incorporated into the model
- Operating rules – including key triggers and transfers, environmental flows, minimum flows and riparian releases, restrictions triggers and demand reduction and augmentation options.
- Model calibration and validation, modelling setup practices
- Yield modelling approach

Changes made since the last review and in response to 2021 and 2025 review recommendations are extensive. For this reason, the review was undertaken by looking at all key model elements and then cross-referencing them with changes made since the last review or in response to the 2021 and 2025 review recommendations where relevant. Given that yield modelling is undertaken using a monthly timestep using stationary demand and input assumptions, the review was focussed on the monthly rather than the daily components of scripts and the stationary rather than dynamic elements of the model. Augmentation options were not reviewed as they do not form part of the yield assessment.

In addition to classifying individual recommendations by their relative level of effort (low, medium, high) and priority (low, medium, high) based on their potential impact on model accuracy and/or estimates of yield under climate change, the review of the WATHNET model and yield calculation approach also grouped recommendations as essential checks and corrections (to correct an error or omission, or to perform checks to confirm whether or not an error or omission has occurred), opportunities for improvement (to enhance model defensibility, model usability, or improve documentation) and industry/modelling practice (to retain a current modelling practice, or to explore and potentially transition to a new modelling practice, as informed by contemporary good practice in the industry).

A letter H, M, or L is included in brackets after each recommendation in the body of this chapter to denote it as being a relatively high, medium, or low priority, and all recommendations are listed by group in Section 6.3. The relative level of effort to implement the recommendation is estimated in Section 6.3.

## 6.1.1 Implementation of 2021 and 2025 review recommendations

The 2021 review (WREMA, 2021) checked the correctness of the WATHNET model and its application to yield modelling. The 2025 review (Kuczera, 2025) focussed on a set of specific changes made to the model since the 2021 review as documented in the references provided by WaterNSW for that review, which were labelled Annex A1 (various model changes), Annex B (Upper Nepean Dams Operation Rule Review) and Annex C (proposed method to model rainfall on lake).

For this project the implementation of recommendations from each review was checked and comment made on recommendations yet to be implemented, taking into account subsequent investigations undertaken by WaterNSW, for example the Upper Nepean Operational Toolkit Rule Review (May 2025).

### 6.1.1.1 2021 review recommendations

The recommendations arising from the 2021 review are comprised of two 2016 review recommendations that were yet to be implemented and four new recommendations as follows:

- 2016 recommendations yet to be implemented:
  - Adoption of a harvest node to represent the Shoalhaven transfers
  - Constraining the releases from the dams (including environmental flows) to outlet capacity, with the capacity based on the storage level
- New 2021 recommendations:
  - Fitzroy Falls Transfer: Correct the transfers scripts with global variable “G067” used in place of “G035”.
  - Transfers from Wingecarribee Dam: Remove the spill capacity constraint.
  - Pheasants Nest and Broughton’s Pass Environment Release: Adopt the eflow values estimated for the harvest nodes at the upstream dams for use at Pheasants Nest and Broughton’s Pass, with new sampled values only for the intermediate catchments.
  - Releases from Metropolitan Dams: It is recommended that the three release arcs for the Metropolitan Dams be amended to separate spills from releases for better accounting of releases and spills.

Table 6-1: Summary of 2021 review recommendations

	2021 Recommendation	Current status	HARC 2026 review comment
1	Represent Shoalhaven transfer with harvest node	Included in model but not implemented	The 2021 review report noted that WaterNSW had attempted to implement a harvest node to represent the Shoalhaven transfers but that results were erratic. The harvest node was updated as part of 2021 review. The WaterNSW memo <i>Harvest Node Method for environmental flow releases</i> demonstrates that the equation method and the harvest node method applied to Shoalhaven transfers produces very similar results on a monthly timestep. The conclusion that the equation method be retained is sound for historic and current climate, but it is recommended that the same test be repeated using inflows under climate change to ensure the same relationship applies under climate change.

	2021 Recommendation	Current status	HARC 2026 review comment
2	Storage outlet capacity constraints	Refer Section 6.1.1.2	An approach was recommended in the 2025 review. This has been implemented for all storages except Wingecarribee and Warragamba. Some enhancements have been suggested as part of this review. Refer to Section 6.1.1.2 for details
3	Fitzroy Falls Transfer replace G035 with G067	No longer relevant	This recommendation relates to a rule to reduce environmental flow releases from Tallowa Dam by 50% when certain conditions occur. This recommendation does not apply given current Water Sharing Plan rules for Tallowa eflow releases.
4	Transfers from Wingecarribee Dam – Remove capacity constraint	Constraint removed	Recommended that some redundant code that constraints spills when storage fraction <0.9 be removed.
5	Pheasants Nest and Broughton's Pass Environment Release	Included in model but not implemented	The recommendation is to adopt factored harvest node values estimated for the upstream dams with new sampled values only for the intermediate catchments. Examination of Pheasants Nest eflow arc shows that this has been implemented in the script for the case where eflows are calculated using harvest nodes, but this option is not switched on in the model.  The WaterNSW memo <i>Harvest Node Method for environmental flow releases</i> demonstrates that the equation method and the harvest node method applied to environmental flows produces very similar results on a monthly timestep. The conclusion that the equation method be retained is sound for historic and current climate, but it is recommended that the same test be repeated using inflows under climate change to ensure the same relationship applies under climate change.
6	Releases from Metropolitan Dams – Separate spills from releases		An approach was recommended in 2025 review to set spill arc capacity to a large number and spill arc costs to 15,000,000. This has been implemented for Nepean, Avon, Cordeaux, Cataract and Wingecarribee. Other spill arcs have different cost settings. It is recommended that this be resolved. This is discussed further in Section 6.1.3.2.

### 6.1.1.2 2025 review recommendations

The implementation of 2025 review recommendations was checked and comment made on those recommendations yet to be implemented, as detailed in Table 6-2 below. Subsequent investigations undertaken by WaterNSW were also taken into account, for example the Upper Nepean Operational Toolkit Rule Review (May 2025).

Table 6-2: Summary of 2025 review recommendations

No*	Recommendation	Section in 2025 Implemented? review report		Current status	HARC 2026 review comment
1	Edit scripts to check for invalid settings whenever scripts are revised	3.1.2	Yes	20 instances of fatal errors set (arcs Warragamba pipeline1, Tallowa to Fitzroy Falls, start-of-replicate settings, subroutines EFlowArcCalc, GetDemand, OptionConst	Continue to add as scripts are edited
1	Echo Settings in a log file	3.1.3	No		Retain recommendation for model setting system table clarity
2	Unit Conversion Factor	3.1.4	No		Retain recommendation
	Starting Storage options 1 - read start storage from end of last replicate 2 - read start storage from system table 3- Set as fraction of TSS	3.2	Yes	Code implemented in start of replicate script	
3	Dam Outlet Capacity Script	3.3	Partially	Partially implemented	Refer Section 6.1.1.2
	Standardise demand node script	3.4.1	Yes	Subroutine getDemand implemented	
	Nth Richmond Demand supply paths – relax constraint and use reservoir water values to drive releases	3.4.2	Partially	Arc capacities have been changed but not implemented in the way suggested in the 2025 review. Arc supplying Nth Richmond demand set to 300 ML/d capacity Warragamba release arc capacity set to 25 ML/d in summer and 17 ML/d in winter in accordance with the 2023 Water Sharing Plan	Deleted commented out code in script if no longer valid. Document basis of capacity assumptions.
	Change Warragamba spill arc cost	3.4.2	No	Not implemented	Update as per comment in Section 6.1.3.2
	Restriction policy script – add subroutine to improve efficiency	3.4.3	No	Not implemented	Worthwhile retaining recommendation to improve efficiency
	Restriction policy script – add subroutine to improve efficiency, rewrite using do loops and global vectors	3.4.3	Yes	getResLevel subroutine simplified	
	Restriction policy script – consider rising trigger	3.4.3	No	Not implemented	Only needed if restriction level instability is a big issue in the model. If so, adoption of a different rising trigger should be linked to actual practice. Could also consider a time based trigger (e.g. must be at a level for >1 month to change).
	Restriction policy script – global variable restlevel	3.4.3	No	Not implemented	Worthwhile retaining recommendation to help with visualisation
	Demand shortfall arcs change	3.4.4	Partially	All demand nodes changed to 20 shortfall arcs but incremental penalty not set to 100,000	Demonstrate that the lower incremental penalty of 25,000 is sufficient to cause shortfall sharing or change to 100,000
	SDP1 Script – change style, add g070 calc	3.5	No		Low priority, no change to results
4	Modelling Deep Storage – use high cost carryover gain to implement deep storage	3.6	Partially	Implemented for Avon, Woronora, Fitzroy Falls and Prospect	Refer discussion Section 6.1.1.2
	Modelling Deep Storage –Edit arc cost to allow option 8 deep storage access	3.6	yes	Implemented on Avon release arc	
5	Spill Arc Operation – modify to pass spills only. Apply 15,000,000 cost	3.7	Partially	Implemented at all storages except Prospect, Fitzroy Falls and Warragamba. Refer discussion Section 6.1.3.2	Update all to 15,000,000 to avoid them being overridden by demand shortfall costs (10,000,000).
6	Remove Duplicate Code in option scripts	3.8.1	Yes	Option scripts have been simplified and moved to subroutine getOptionArcCap. Script in subroutine matches suggestion in review report	
7	Use option dependent mapping – remove hard coding of option numbers	3.8.4	No		Worthwhile retaining recommendation to minimise coding errors. Not needed if next recommendation is taken up
8	Use robust naming convention – use common name in arcs and system tables	3.8.4	No		Worthwhile retaining recommendation to minimise coding errors
9	WSP2023 Eflow rules – use antecedent flows	3.9	No		Not relevant for monthly timestep modelling
	Use sub routine to reduce duplication	3.9	Yes	Subroutine EFlowArcCalc implemented	
10	Nepean Avon transfer rule review	4	No		Refer Section 6.1.1.2
11	Recalibrate water values using emoga	4	No		Refer Section 6.1.1.2
12	Adjust dam wall to lake bed inflows using an area factor	5.2	Yes	Adjustment made at reservoir inflow nodes using a script and subroutine	Refer Section 6.1.1.2. 2025 recommendation has been applied, however an alternative approach is recommended in future
	Compute net inflow to the lake to allow for net rainfall impacts on the lake		Yes	Net evap applied at reservoir nodes	
13	Regenerate stochastic data using pre-dam inflows	5.2	Yes	Refer hydrology review in Section 4	
	Set maximum replicate length to dynamic simulation period	6.1	Yes	Not recommended by HARC. Refer hydrology review in Section 4	
	Extension of hydrology using rainfall-runoff models	6.2	No	Refer hydrology review in Section 4	

\* Recommendation number as listed in the 2025 review

## Dam outlet capacity

The 2025 review recommended an approach to representing the physical outlet capacity constraint of a dam in such a way that it applies to both the eflow and supply releases from the dam. It involved placing a third arc downstream of these two release arcs. It also recommended an equation on the downstream arc that calculates outlet capacity as a function of storage fraction (% full). The scripts for the eflow and supply release arcs can then be simplified to remove the outlet capacity algorithm.

Examination of the WATHNET system file shows that this three-arc layout has been implemented for Nepean, Avon, Cordeaux and Cataract storages. It has not been implemented for Wingecarribee or Warragamba. It is recommended that this layout also be implemented for Wingecarribee and Warragamba.

The scripts applied have also been examined. An example for Cordeaux is shown in Figure 6-1. This script calculates the storage fraction using initial volume in the first iteration then uses average volume thereafter.

Concentrating on the monthly case (g006=2) the script is deriving a maximum release capacity from the eflow system table of 660 ML/d. Capacity is then calculated as a function of storage fraction with a constant added. It is recommended that the basis of this equation and constant be documented.

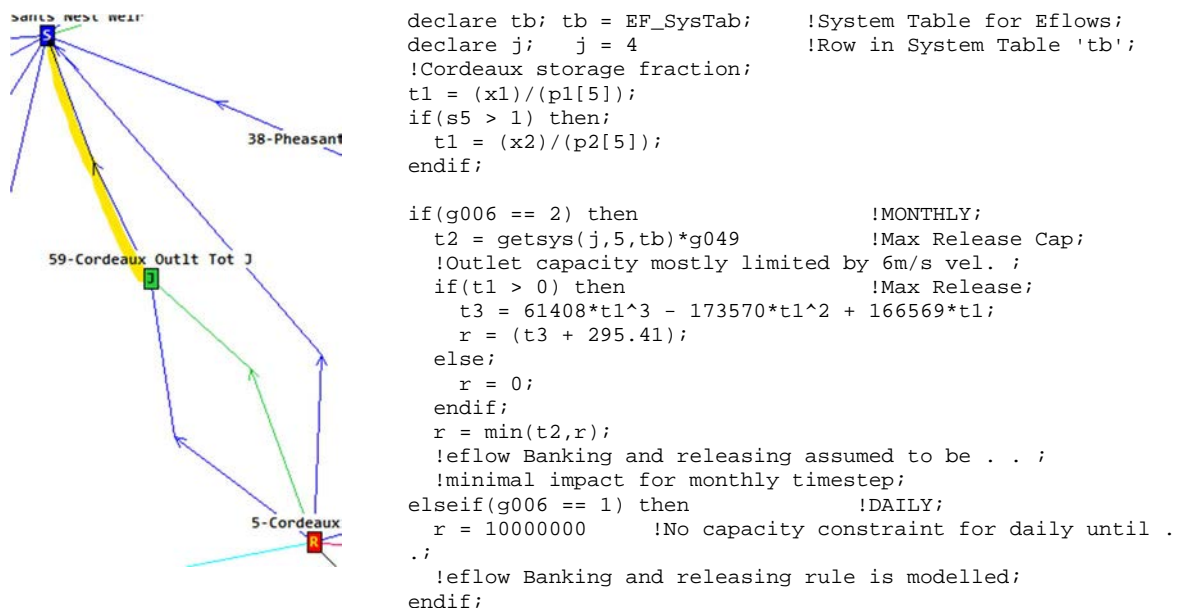
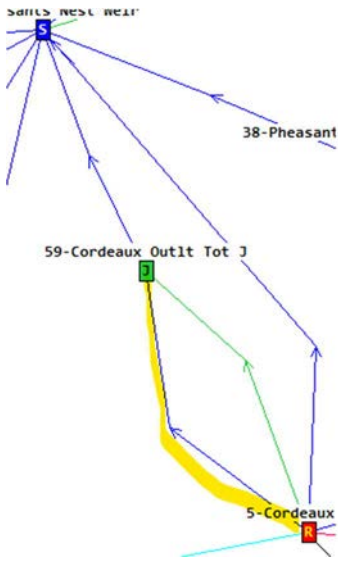


Figure 6-1: Cordeaux total release arc (note: some words in the above code spelled out in this figure by HARC for general readability)

An example of the eflow arc scripting is shown in Figure 6-2. It is evident that the hydraulic capacity calculation has been removed from this arc as recommended in the 2025 review.



```

declare j; j = 4 !Row in System Table 'EF_SysTab';

if(s5 == 1) then;
! Sample from harvest data if appropriate;
! In next version sample harvest data in subroutine;
if(stepFlag == MONTHLY .and. eflwEqn == eHARVEST) then;
d1 = x1;
arcap(s33) = harvec(2,1,1);
EF_Cord = arcap(s33) !to be used in BP eflow calc.;
endif;
! Determine eflow and save in arcap(s33);
d1 = x1;
d2 = j;
call EFlowArcCalc;
endif;

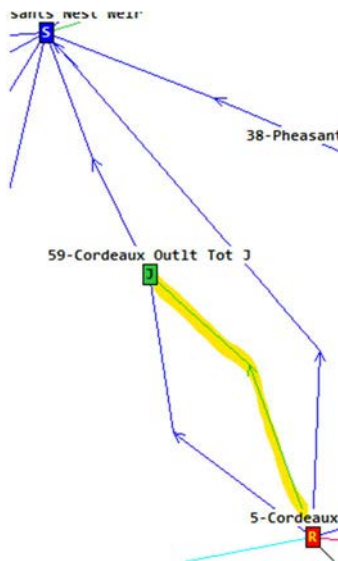
r = arcap(s33);

t1 = getsys(j,6,EF_SysTab)*g049/g007 !Min Rele requirement;
if(r < t1) r = t1;

```

Figure 6-2: Cordeaux e-flow release arc (note: some words in the above code spelled out in this figure by HARC for general readability)

An example of the release for supply arc scripting is shown in Figure 6-3. It is evident that the hydraulic capacity calculation has been removed from this arc as recommended in the 2025 review, however, as mentioned above, maximum release capacity from the eflow system table.



```

declare tb; tb = EF_SysTab; ! System Table for Eflows;
declare j; j = 4 ! Row in System Table 'tb';

r = getsys(j,5,tb)*g049/g007 !Max Release Cap;
!Outlet capacity mostly limited by 6m/s velocity ;

```

Figure 6-3: Cordeaux release for supply arc (note: some words in the above code spelled out in this figure by HARC for general readability)

### Dead storage

The 2025 review suggested using a high cost on carryover gain arcs on reservoir nodes to represent dead storage. HARC's review found that this had been implemented at Avon, Woronora, Fitzroy Falls and Prospect storages. At Warragamba, Cataract, Cordeaux and Nepean reservoirs the dead storage is small (<1% of storage capacity) so cannot be successfully represented given the integer-based nature of carryover gain arcs. It is recommended that dead storage be added at these sites if this limitation is resolved in future.

In the case of Wingecarribee, allowance for dead storage is instead implemented on Glenquarry Cut, the transfer arc and the environmental release arc. At Tallowa the arc to Fitzroy Falls “Tallowa -3m” option applies a lower limit of 68,200 which is less than dead storage. The dead storage volume of 82,500 applies to the “Tallowa -1m” option. No dead storage is applied to the environmental and riparian release. WaterNSW have advised that there is a differentiation between the pumps within the lake used for hydropower generation and to facilitate Shoalhaven transfers, and releases from the actual dam structure such as the low-level outlet for downstream riparian and Shoalhaven water releases.

HARC recommend that a consistent approach to representing dead storage be used where possible. This should be at the node if dead storage is consistent for all outlets or on each outlet arc if different or if dead storage pumping is an option. The Expert Panel recommended that dead and active storage be explicitly specified within the model.

It is also noted that a dead storage option will be included in the reservoir node in the next version of WATHNET. Use of this should be considered for all storages where dead storage pumping is not an option.

### **Nepean Avon transfer rule review**

The Upper Nepean Operational Toolkit Rule Review undertaken by WaterNSW proposed changes to the Upper Nepean operating rule guidance within the Operational Toolkit. Changes were based on adjustments to storage triggers in WATHNET. Throughout the course of the 2025 review, these rules were checked and an investigation requested into how transfers change with the number of demand shortfall arcs increased and with hard coded transfer rules relaxed.

Based on the outcomes of that investigation the 2025 review report recommended that the proposed rules be adopted as an interim measure and that (1) further investigation be undertaken into the representation of the Nepean Avon pumped and gravity transfer using the daily model, suggesting that a harvest node may be required, and (2) that recalibration of water values be undertaken (refer to Section 6.1.5.5 for an explanation of water values).

While WATHNET can be updated to incorporate optimised water values under current infrastructure, water values are neither transparent nor easily updated. It is also important to recognise that operators will, in general, follow a set of more simplified operating rules, taking into account other considerations not represented in the model (e.g. shandy requirements to manage water quality). With this in mind it is recommended that newly optimised water values be derived as recommended, but that these be considered in conjunction with operator practices to come up with a new set of agreed rules consistent for both operators and the model, to be hardcoded if/where variance from water values is necessary.

### **Inflow adjustments**

As recommended in the 2025 review, scripts are included in the model for selected reservoirs to adjust inflows from the nodal data file to be applicable at either the lake boundary or at the dam wall. The current setting in the model is to derive inflows at the lake boundary by factoring inflows down by the area inundated as a proportion of total catchment area. Net evaporation impacts at storage are then applied.

In relation to the 2025 review recommendation this has been correctly implemented in the model, however as discussed in detail in Section 4 of this review, it is recommended that consistent inflows be derived for input to the nodal input file (and stochastic data generation).

### 6.1.1.3 Findings and recommendations

It was found that the majority of recommendations from the 2021 and 2025 have been implemented. Where they have been partially implemented or not implemented, recommendations have been retained, removed or updated by HARC as part of this review.

#### **Recommendations (and their priority as high, medium, or low):**

- Shoalhaven transfer – recheck performance under climate change inflows (M)
- Storage outlet capacity constraints – implement for Wingecarribee and Warragamba (M)
- Pheasants Nest and Broughton’s Pass Environment Release – recheck performance under climate change inflows (M)
- Spill arc costs – implement for remaining dams (L)
- Invalid script settings – Continue to add as scripts are edited (L)
- Echo Settings in a log file – retain recommendation (L)
- Unit Conversion Factor – retain recommendation (L)
- Documentation – document basis of equations (e.g. dam outlet hydraulic calcs) (H)
- Restriction policy script – add subroutine to improve efficiency (L)
- Different rising restriction trigger – consider if restriction level instability is a big issue (L)
- Demand shortfall arc incremental penalty – Demonstrate that the lower incremental penalty of 25,000 is sufficient to cause shortfall sharing or change to 100,000 (M)
- Deep (dead) storage – use a consistent approach where possible on reservoir node or outlet arcs as required. Include explicit representation of active storage. Consider use of dead storage reservoir node in next version of WATHNET, including adding representation of dead storage for Warragamba, Cataract, Cordeaux and Nepean (M)
- Active storage – include explicit representation of active storage (L)
- Use option dependent mapping – retain recommendation (L)
- Use robust naming convention – retain recommendation (M)
- Nepean-Avon transfer rule – consider updating water values in conjunction with operator practices to define a new set of agreed rules (M)
- Inflow adjustments – rederive consistent inflows for input to nodal file (H)

### 6.1.2 Other model changes since 2021 review

Model changes made since 2021 are numerous. These were checked against settings in the current model and marked as superseded where required.

Where changes were still current, information in the log of model changes was used to inform comments in this report.

### 6.1.3 Overall model review - The physical system

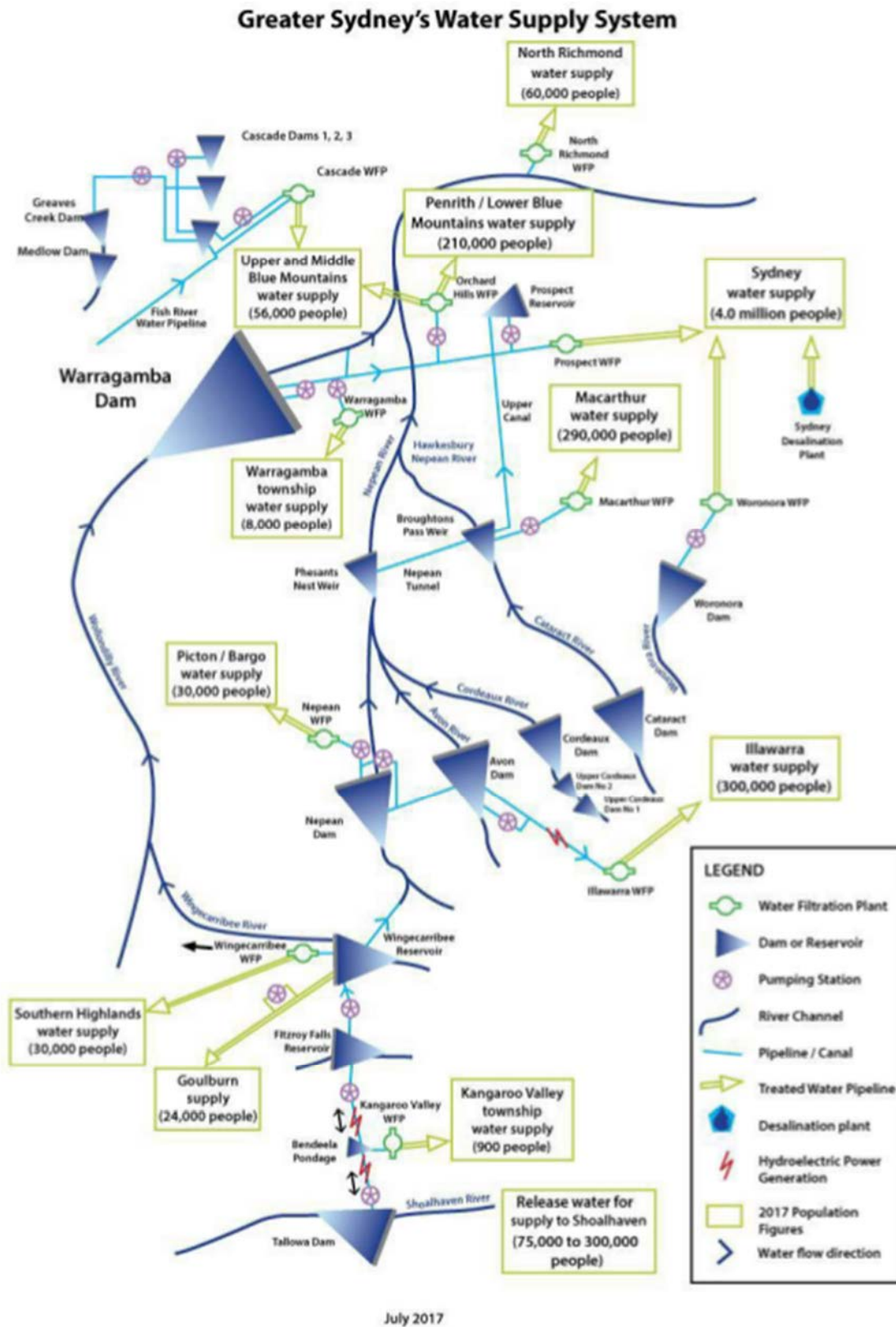


Figure 6-4: System schematic

### 6.1.3.1 Model layout and discretisation

#### Model extent

In general, the model focusses on the representation of headworks storages and demands. Waterways are represented where they are used to transfer flows for supply. This includes the reach between Wingecarribee and Warragamba, and downstream of the Upper Nepean dams and Warragamba Dam to the North Richmond offtake.

#### Transfer losses and local inflows

There are no losses included in the model associated with the transfer of flows for supply along river reaches or canals. A number of transfer reaches also do not include local inflows. Presumably this assumption has been made on the basis that local inflows and losses largely cancel each other out. This may, however, not be the case under future climate change.

Model defensibility would be enhanced if it is demonstrated that this assumption has been investigated for the following reaches:

- Wingecarribee to Nepean (Glenquarry Cut) (loss)
- Wingecarribee to Warragamba (loss)
- Nepean/Avon/Cordeaux to Pheasants Nest Weir (loss)
- Cataract to Broughtons Pass Weir (loss)
- Warragamba to North Richmond offtake (loss and local inflow)
- Pheasants Nest and Broughtons Pass weirs to Nth Richmond offtake (loss and local inflow)
- Upper Canal (loss)

It would also be worth considering inclusion of local inflows and losses where they are absent so the impact of climate change can be captured.

#### Impact of river diverters and interception activities

The model makes allowance for riparian releases from a number of reservoirs including Tallowa (65 ML/d) and Wingecarribee (1 ML/d), but does not explicitly represent the impact of river diversions on transfers of flow for supply along river reaches (e.g. from the Upper Nepean dams to the weirs or from Warragamba to Richmond) or the impact of interception activities such as farm dams on local catchment inflows.

The magnitude of both river diverters and farm dam interception should be small and have little impact on yield, but model defensibility would be enhanced if the basis of existing assumptions is stated and it is demonstrated that impacts elsewhere are negligible and will remain so under climate change.

#### Discretisation and level of detail

Some lumping of system features is evident in the model, for example the balancing storage at Bendeela Pondage is not explicitly represented. This is a reasonable assumption on a monthly timestep given the typical magnitude of transfers. There could be merit however in representing this storage in future if, for example, pumps upstream and downstream were to be augmented in stages.

If this is represented in future, Kangaroo Valley demand from Bendeela Pondage should also be represented.

The supply to Goulburn and Bowral out of Wingecarribee Reservoir is represented as a single demand node in WATHNET, but the system schematic suggests Bowral is clearwater gravity supply and Goulburn is raw water pumped supply. If so, there may be merit in separating out these two supply streams to (a) pick up pump hydraulics/costs and (b) account for future changes to losses if the water filtration plant is upgraded.

It is noted that Upper Cordeaux dams 1 and 2 are lumped with the main dam which is a reasonable assumption.

The 2023 Water Sharing Plan notes there is a volume of water available to Origin Energy for hydro-electric power generation between Fitzroy Falls and Tallowa. WaterNSW have advised that transfer assumptions take this constraint into account

### **Representation of demand zones and transfer system**

The Expert Panel noted that the representation of demand zones and the transfer system in the model was coarse. The stakeholder response from Sydney Water raised concerns about the ability of the system to supply demand when storage drops below 30%. The GSDRP refers to high risk nodes in extreme drought. These concerns raise the question whether the WATHNET model adequately represents the transfer system and demand zones. Two principles were provided by the Expert Panel to guide representation of demand zones and transfer system:

1. Explicitly represent capacity limits on all current and future bulk transfer arcs. A demand shortfall may occur if there is insufficient supply or if there are transfer constraints. In the latter case investments will be needed to avoid such shortfalls
2. Ensure that the bulk transfer arcs supplying a demand node can physically deliver water to the whole physical region represented by the node. If this is not the case, then more granularity is needed. This is particularly important in zones that experience high growth and when adding climate-independent supply sources which may only serve a limited demand zone.

### **Timestep**

It is understood that the model is run on a monthly timestep for the purposes of yield modelling. When using a monthly timestep, allowance must be made for locations where highly variable daily flows impact monthly water availability. This can be done in WATHNET using a harvest node. These are discussed further in Section 6.1.5.1. These would be switched off when the model is run on a daily timestep. There are a wide range of additional considerations when undertaking daily timestep modelling. These are outside the scope of this review.

**Recommendations (and their priority as high, medium, or low):**

- Confirm that net local inflows and losses from transfers between storages or to offtake points are negligible, and would remain so under climate change scenarios, otherwise explicitly represent these losses and net local inflows (M)
- Confirm that the current and future impact of diversions and interception activities is negligible, or otherwise seek to quantify and document this influence on system inflows and transfers (L)
- Document the need or otherwise to represent hydro-electric transfers between Fitzroy Falls and Tallowa (L)
- Check the need to represent demand zones and the transfer system in more detail (M)

### 6.1.3.2 Representation of infrastructure

#### Storages

Storage characteristics, as defined in the model, are shown in Table 6-3 along with HARC's review comments on model settings. Most comments are minor "housekeeping" suggestions, however there is a need to reconcile capacity and dead storage volumes for a couple of storages, and consider applying climate impacts on storage in one case. It is also recommended that the 0.3 m drawdown of Warragamba be represented separate to the spill arc. Storage outlet capacity is discussed in Section 6.1.1.2.

#### Carryover arcs

The high number of carryover arcs set for most storages indicates that sharing of water between storages as required is encouraged. The small number of carryover arcs set for Fitzroy Falls, Tallowa and Prospect means that water will be retained in these storages and only transferred according to operating rules. The use of carryover arcs to drive sharing of water between storages ("water values") is discussed in detail in Section 6.1.5.5.

#### Rating tables

Storage rating tables as represented in the model were reviewed. These look reasonable. A check should be made to ensure the rating tables used for CMCR calculations match the rating tables used in the model. If rating tables have changed over time this should be reflected in CMCR for inflow derivation, but only the most up to date table used in WATHNET.

#### Dead storage

It was noted that there is some inconsistency in the application of deep or dead storage across reservoir nodes, outlet arcs or within scripts. It is recommended that this be reconciled where required and a single reference point (i.e. system table 5) used where possible.

Where dead storage is different for different outlets this should be taken into account on the respective outlet arcs. Representation of dead storage is discussed in more detail in Section 6.1.1.2.

## Spills

A cost of 15,000,000 has been implemented on spill arcs for Wingecarribee, Nepean, Avon, Cordeaux and Cataract storages, in line with the 2021 and 2025 recommendation to amend spill arcs to only carry spills, not releases (refer Section 6.1.1).

Fitzroy Falls spill arc has a cost of 1,000,000, Prospect spill arc has a cost of 2,000 and Warragamba spill arc has a cost of -5. It is recommended these be updated to also be 15,000,000 to avoid them being overridden by demand shortfall costs (10,000,000).

### **Recommendations (and their priority as high, medium, or low):**

- Resolve difference in Warragamba dead storage and capacity in node and system table (M)
- Represent Warragamba release to allow for drum gate in a separate arc (L)
- Reconcile values in Prospect node, notes and system table 5 (M)
- Apply dead storage to Tallowa releases if required. Update to 62,800 in the system table if this is the true dead storage (M)
- Adopt dead storage at node wherever possible when the next version of WATHNET is released (M)
- Check model and CMCR rating tables match (M)
- Test and if suitable apply cost of 15,000,000 to all spill arcs (L)

Table 6-3: Storage characteristics in WATHNET Model Version Run 43\_Syd25

Storage	Capacity (ML)	Dead store (system table 5, ML)	Net evaporation on node	Number of carryover arcs	Representation of dead store (% of storage capacity with high carryover gain)	WATHNET notes on node	Local Inflow	Arcs out	Review comment
Warragamba	2,069,000 (node) 2,069,160 (system table 5)	4,482	Net_Evap_Warragamba	20	Not implemented	Warragamba storage volume from bathymetry Sept 2014. Total Storage Capacity is 2069GL. Top 0.3 m is released to avoid wave action opening drum gate; effective operating storage is 2047GL. top 0.3 m is released in spill arc	Inflow_Warragamba Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Nth Richmond release	Resolve difference in deep storage and capacity in node and system table Release to allow for drum gate should be represented in a separate arc, not the spill arc Ensure net evap data set is consistent with that used for the water balance on storage calculation
Woronora	72,657	3,121	Net_Evap_Metro Dams	20	4%	Modified Woronora volume 72,657 ML (Sept 2014). 3,000 ML Deep storage	Inflow_Woronora Inflow script adjusts inflow to lake boundary	Spill arc Enviro release	
Cataract	97,190	180	Net_Evap_Metro Dams	20	Not implemented	Total Storage 97,190 ML Dead storage 180 ML	Inflow_Cataract Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Supply release (total release)	Ensure net evap data set is consistent with that used for the water balance on storage calculation
Cordeaux	93,790	0	Net_Evap_Metro Dams	20	Not implemented	none	Inflow_Cataract Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Supply release (total release)	Ensure net evap data set is consistent with that used for the water balance on storage calculation
Avon	213,450	71,220	Net_Evap_Metro Dams	20	33%	71,220 ML Deep Storage_June2022/Apr2023 in WATHNET 213,450 ML Total Storage June 2022 142,230 ML Operating Capacity June 2022	Inflow_Avon Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Supply release (total release)	Ensure net evap data set is consistent with that used for the water balance on storage calculation Remove commented out code in reservoir script if this won't be used in future
Nepean	68,100	370	Net_Evap_Metro Dams	20	Not implemented	none	Inflow_Nepean Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Supply release (total release)	Ensure net evap data set is consistent with that used for the water balance on storage calculation Remove commented out code in reservoir script if this won't be used in future
Wingecarribee	31,632	1,752	Net_Evap_Fitzroy Falls	20	Not implemented	Storage area based on 2011 Bathymetry Carryover gains adjusted to reflect operating window of 0 - 2m below FSL. Deep Storage included to minimise instability (Crashing) Deep Storage 1752 ML	Inflow_Wingecarribee Inflow script adjusts inflow to lake boundary	Spill arc Enviro release Winge-Warragamba transfer	Ensure net evap data set is consistent with that used for the water balance on storage calculation Remove commented out code in reservoir script if this won't be used in future
Fitzroy Falls	22,920	12,970	Net_Evap_Fitzroy Falls	3	57%	none	Inflow_Fitzroy Falls Inflow script adjusts inflow to lake boundary	Spill arc Enviro release FF to Wingecarribee transfer	Ensure net evap data set is consistent with that used for the water balance on storage calculation
Tallowa	90,000	82,500	Net_Evap_Fitzroy Falls	4	Not implemented	none	Inflow_Tallowa Inflow script adjusts inflow to lake boundary	Spill arc Enviro release To Fitzroy Falls	Ensure net evap data set is consistent with that used for the water balance on storage calculation
Prospect	33,330 (node) 48,220 (system table 5)	14,890	Unassigned	4	31%	Storage Area Table updated in March 2025 Total Volume 47,032 ML Deep Storage 14,175 ML Prospect Inflow and evaporation not modelled.	Unassigned	Spill arc Prospect pipe	Need to reconcile values in node, notes and system table 5. Need to represent local inflows and the impacts of rainfall and evaporation on storage

## Pipes, pumps and channels

Transfers along pipes and channels were examined to determine if/how capacity was set. This along with transfer rules are discussed in detail in Section 6.1.5.1.

In general, it is recommended that capacities of pipes, pumps and channels be included in the model where they have not been specified to ensure capacities are not limiting under yield runs and/or under future climate.

### Recommendations (and their priority as high, medium, or low):

- Impose physical capacity constraints where they are not currently specified (H)

## 6.1.4 Overall model review - Model inputs

### 6.1.4.1 Inflows and climate inputs

The derivation of model inflows and climate inputs is addressed in detail in Section 3. The WATHNET model review considered how inflows and climate inputs are incorporated into the model, adjustments made at inflows nodes, and compatibility with WaterNSW's inflow calculations.

As noted in Table 6-3 and discussed in detail in Section 6.1.1.2, inflows to inflow nodes above storages are adjusted to apply at the lake boundary.

At some locations inflows are input as a function of other inflows for example Pheasants Nest Weir local catchment inflow is  $0.64 * \text{Avon Inflow}$  and Broughtons Weir local catchment inflow is  $0.2 * \text{Cataract Inflow}$ . The log of model changes suggests that these factors are based on daily inflows from 1900 to 2020, received from DCCEE in Jan 2025. This should be included in model documentation. There is also an inflow of 43 ML/d at the Hawkesbury Nepean confluence representing recycled water from St Marys. This should also be documented.

It is noted that no local inflows or climate impacts on storage are included for Prospect Reservoir. If this is because it is felt that these impacts cancel out under current climate, it is worth considering including these, as this may not be the case under future climate.

Where net evaporation is input at storages it is important that these are the same as the evaporation and rainfall depths used for water balance on storage to calculate inflows (recognising that this will alter under climate change).

Section 3 recommends a consistent inflow derivation approach. If this results in the changes to the lake boundary adjustment this should be updated in the model.

**Recommendations (and their priority as high, medium, or low):**

- If inflow changes result in the changes to the lake boundary adjustment this should be updated in the model (H)
- Ensure the net evap data set is consistent with that used for the CMCR water balance on storage calculation (H)
- Document inflows derived within the model (at weirs and St Marys) (M)
- Represent local inflows and the impacts of rainfall and evaporation on Prospect Reservoir to allow change under future climate (M)

### 6.1.4.2 Demands

Demands input to the WATHNET model are provided by Sydney Water. For yield runs the annual demand is split into the relevant demand zone and a climate based pattern applied. Reduction in demand due to restrictions is applied by calculating a restriction demand fraction. Derivation of restricted demand is addressed in Section 6.1.5.3.

$$\text{Demand} = \text{seasonal fraction} * \text{demand zone disaggregation fraction} * \text{restFrac} * \text{annual demand}$$

Where:

- *annual demand* = annual demand for Sydney in megalitres, excluding Bowral & Goulburn
- *demand zone disaggregation fraction* = share of total annual demand in that zone
- *Seasonal fraction* = climate based pattern
- *restFrac* = restriction demand fraction

**Annual demand** - It is recommended that details of the annual demand derivation are included in model documentation.

**Demand zone disaggregation fraction** - Demand zone disaggregation is specified in system table 1. Notes in the WATHNET model state that the disaggregation is based on Sydney Water's demand projection Run 70 (2024). It is recommended that details are included in model documentation.

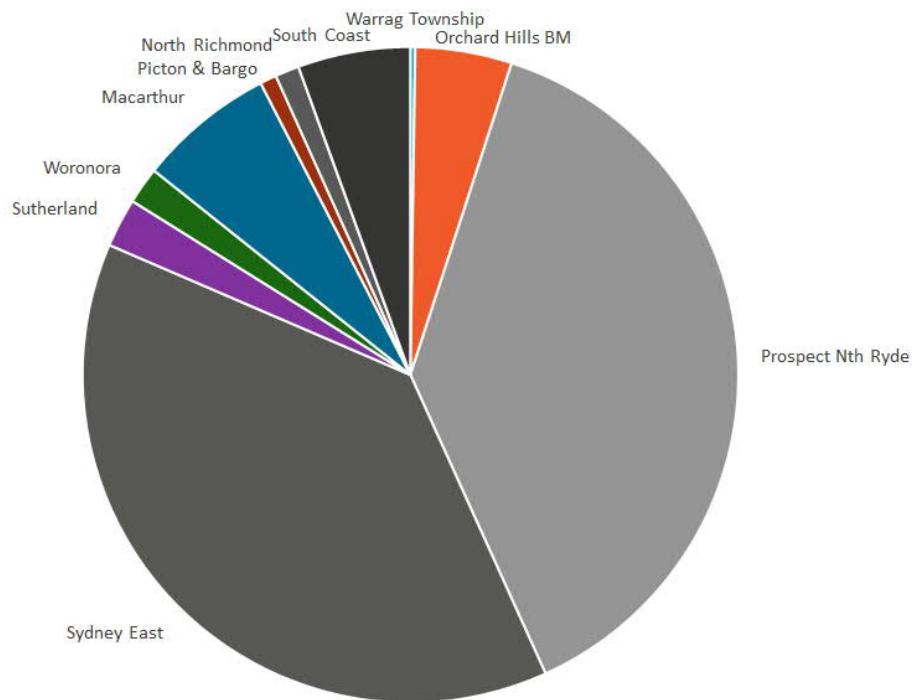


Figure 6-5: Demand zone disaggregation based on Sydney Water demand projection Run 70

**Seasonal fraction** - The seasonal fraction is a monthly climate-driven pattern derived by Sydney Water using demand models with current population and consumption patterns and weather from the BOM's gridded historical datasets from 1909-2024 (demand projection Run 70, 2024). It is recommended that details are included in model documentation.

WaterNSW advised that the seasonal fraction timeseries forms an input to the stochastic data generation process and a stochastically generated data set if obtained. It is recommended that this process be documented and a check made of whether the relationship between historic inflows/climate and historic seasonal fraction is maintained in the stochastic data. If not, a relationship could be derived between seasonal fraction and a suitable climatic driver (e.g. temperature) and this relationship be used to apply seasonal fraction to demands for the stochastic runs. This will also be useful for climate change runs.

Demands are calculated in the model using the `getDemand` subroutine with the exception of Bowral and Goulburn. In this case for yield runs,  $demand = seasonal\ fraction * restFrac * annual\ demand$ , where annual demand is 7,020 ML/yr. For consistency it is recommended that this demand be represented using the `getDemand` subroutine.

All demand nodes have 20 shortfall arcs to ensure the sharing of shortfalls when they occur.

An expert panel member outlined an alternative demand model for consideration that utilises climate inputs and soil moisture tracking. This could be implemented using scripts within WATHNET. While review of how demands are derived is outside the scope of this project this feedback is included here for future consideration by WaterNSW and Sydney Water. This may lead to a change to existing accountabilities and would require both agencies to agree upon model governance changes to

facilitate its adoption. It is also noted that calculation of demands within the model using climate variable demand factors means demand changes under climate change are automatically implemented.

Table 6-4: Demands in WATHNET

Demand node	Supply sources	Demand script
Woronora	Woronora, Prospect+desal	getDemand subroutine
Sutherland	Woronora, Prospect+desal	getDemand subroutine
Sydney East	Woronora, Prospect+desal	getDemand subroutine
Prospect+North+Ryde+Liverpool	Prospect+desal	getDemand subroutine
Orchard+Penrith+BM	Warragamba	getDemand subroutine
Warragamba Township	Warragamba	getDemand subroutine
South Coast	Avon	getDemand subroutine
Picton and Bargo	Nepean	getDemand subroutine
Bowral and Goulburn	Wingecarribee	for yield runs demand = seasonal fraction * restFrac * annual demand (7020)
Macarthur	Cataract, Broughtons Pass	getDemand subroutine
North Richmond	Hawkesbury R	getDemand subroutine

**Recommendations (and their priority as high, medium, or low):**

- Include derivation of annual demands, demand zone disaggregation and seasonal factors in model documentation, including stochastic generation (M)
- Check relationship between historic inflows/climate and historic seasonal fraction is maintained in the stochastic data. If required, derive a relationship as a function of climate to determine climatic factors for use in synthetic runs. (H)
- Use getDemand subroutine for Goulburn and Bowral demand (L)
- Test and if suitable calculate climate variable demand factors in model (M)

## 6.1.5 Overall model review - Operating rules

### 6.1.5.1 Key transfers / triggers

Key transfer rules are documented in Table 6-5 along with review comments. Review recommendations are largely related to setting physical capacity constraints where they apply, documenting the basis of assumptions, and using values set in system tables where possible. It is noted there is some information on outlet capacities in the model change log.

The harvest node in WATHNET uses random sampling to allow for the difference between a variable daily flow and the amount that flow sums to across a monthly timestep. The WaterNSW memo *Harvest Node Method for environmental flow releases* demonstrates that the equation method and the harvest node method applied to Shoalhaven transfers produces very similar results on a monthly timestep. The conclusion that the equation method be retained is sound for historic and current climate, but it is recommended that the same test be repeated using inflows under climate change before drawing the same conclusion for climate change runs.

**Recommendations (summary from detailed list in Table 6-5) (and their priority as high, medium, or low):**

- Make arc specific edits as per Table 6-5 (M)
- Document basis of equations used (M)
- Apply pipe/pump/canal/tunnel max capacity (H)
- Remove commented out script if it will not be used in future (L)
- Justify or update cost settings (M)
- Justify tunnel daily to monthly conversion factor of 1 (M)
- Justify canal daily to monthly conversion factor of 0.9 (M)
- Avon to Sth Coast demand - Incorporate in a single arc so single capacity constraint can be applied (L)
- Check Woronora Dam to Sutherland arc is still required now demands all have 20 shortfall arcs (L)

Table 6-5: Key transfer infrastructure and rules

Transfer	Link	Rule / capacity	Review comments
Tallowa to Fitzroy Falls	pump	Equation option selected rather than harvest node. If total storage fraction is less than 75% then pumping is switched on (as per the 2023 Water Sharing Plan). Tallowa -1m sets aside 82,500 ML (unavailable storage for Shoalhaven transfers) Capacity = 1500 ML/d subject to a monthly factor of 0.9 and a monthly max factor of 30,000/45,600ML, subject to check of airspace in Fitzroy Falls. Cost of 10 applied	Edit equation to refer to dead storage in system table. Document basis of factors 0.9 and 30000/45600 (2016 review report mentions 0.9 and 30000). Cost applied on arc should not be required
Fitzroy Falls to Wingecarribee	Pump	If total storage fraction less than 75% then pumping is switched on. No maximum capacity is set. The volume that can be transferred calculated is based on live storage but with 40% of inflows set aside. Dead storage assumption of 10,000 ML does not match system table. Does this volume represent something else?	Set pump maximum capacity for completeness if likely to be limiting over the planning horizon Edit equation to refer to the dead storage specified in the system table Document basis of 0.4 factor on inflows
Wingecarribee to Nepean (Glenquarry Cut)	Canal and river	If total storage fraction less than 75% then switched on. Transfer capped at Wingecarribee dead store. Daily capacity based on system table 10 (SHT run of river capacity)	Remove commented out script if it will not be used in future Document basis of system table 10
Wingecarribee to Warragamba	River	Capacity obtained from system table 10. Check made to ensure volume doesn't drop below dead storage	Document basis of system table 10
Warragamba to Nth Richmond	River	Capacity set to 25 ML/d in summer and 17 ML/d in winter Cost on arc set to -2000 to force this release	17 and 25 ML/d from WSP2023. It is understood from the model change log that these constraints are a limitation at higher demand levels which is offset by St Marys PRW discharged at node 40.
Nepean to Avon tunnel	Tunnel	Gravity: appears that hydraulic limits are being applied based on volume in Avon and Nepean and the volume difference between these storages	Remove commented out script if it will not be used in future. Document basis of hydraulic relationships
		Pumping: switched on in system table. Different pump capacity depending on Nepean volumes. Avon must be less than 55%. Retain 10% in Nepean Capacity = up to 6000 ML/d, allowing for gravity supply	Document basis of hydraulic relationships and on/off assumptions
Nepean to Pheasants Nest	River	Max capacity = 660 ML/d. Notes in the log of model changes state this is the maximum discharge is 2 x 330 ML/d and that this flow is possible for full range from FSL to MOL. The log also states that supply-release will be limited to 50 ML/d below 20% storage to meet local supply needs (both Nepean WFP and Avon transfer for Illawarra supply) but this is not implemented in the model (may be superseded). If Nepean storage fraction < 0.4 If Nepean-Avon pump is available or 0.9 if pump is not available then capacity = 0 (g213, set from system table 8) If Nepean storage fraction < 0.4 If Nepean-Avon pump is available or 0.7 if pump is not available then capacity = 660 and cost = 4,000,000. These rules appear to be based on the Upper Nepean Operational Toolkit Rule Review. Cost is mentioned in model change log, but insufficient detail is included.	Document basis for 0.9/0.7/0.4 triggers and 4,000,000 cost
Avon to Pheasants Nest	River	Max capacity = 660 ML/d. If Avon storage fraction < 0.9 then cost = 4,000,000	Document basis for 4,000,000 cost. Document basis for 0.9 trigger
Cordeaux to Pheasants Nest	River	660 ML/d	
Pheasants Nest to Broughtons Pass (Nepean tunnel)	Tunnel	350 ML/d	Justify tunnel daily to monthly conversion factor of 1
Cataract to Broughtons Pass	River	750 ML/d. If storage fraction < 0.45 then then cost = 4,000,000	Document basis for 4,000,000 cost. Document basis for 750 ML/d and 0.45 trigger
Pheasants Nest and Broughtons Pass weirs to Nth Richmond	River	Unconstrained	
Upper Canal	Canal	550 ML/d subject to a monthly conversion factor of 0.9	Justify canal daily to monthly conversion factor of 0.9 Remove commented out script if it will not be used in future
Warragamba to Prospect	Pipe	Capacity = 1000 ML/d if Warragamba <30% 0 ML/d if Warragamba storage is <22%. If Warragamba > 30% then hydraulic relationship as a function of storage volume	Document basis of hydraulic relationship Remove commented out script if it will not be used in future
Prospect to Sydney supply node (Prospect pipeline)	Pipe	Unconstrained. Sutherland-Woronora cost of 300 applied (sets this as second preference to supply Woronora)	Add capacity constraints for completeness or if likely to become limiting over planning horizon
Sydney supply node to East Sydney	Pipe	Unconstrained	Apply capacity
East Sydney to Sutherland	Pipe	Unconstrained	Apply capacity
Sutherland to Woronora demand	Pipe	Unconstrained. Cost 300 to set as second preference source	Apply capacity

Transfer	Link	Rule / capacity	Review comments
Woronora Dam to Woronora demand	Pipe	Dam to Woronora: 90 ML/d WFP capacity Woronora to Sutherland: switches off if Woronora store <40% Sutherland to Sydney east: 1000 ML/d	Document basis of 40%. 1000 ML/d redundant as limited by WFP capacity
Woronora demand to Sutherland	Pipe	Unconstrained. Turn off if storage fraction < capacity	Apply max capacity. Would be better to include an on/off trigger in system table 16
Woronora Dam to Sutherland	Pipe	Can access spare capacity in Woronora outlet to supply Sutherland supply Cost 2000	The model currently has two supply paths from Woronora Dam to Sutherland, one going via the Woronora demand node and this link which bypasses the Woronora demand node. It is speculated that this arc was implemented to overcome Sutherland shortfalls. It may no longer be required now demands all have 20 shortfall arcs.
Sutherland to East Sydney	Pipe	1000 ML/d labelled as "large capacity" Cost 400 to set as second preference source	Apply capacity
Sydney desal	Pipe	If TSS > 90% then 50 ML/d, >75% then 125 ML/d < 75% 250 ML/d. Cost of -2000 to force supply	Note t10 calc not used
River to Nth Richmond	Pipe	300 ML/d	Document basis
Wingecarribee to Bowral and Goulburn	Pipe	Unconstrained. Turn off if below dead store	Apply max capacity
Nepean to Picton Bargo	Pipe	Unconstrained	Apply max capacity
Avon to Sth Coast demand	Pipe	Minimum: off unless Option 1 turned on Supply: 300 ML/d labelled as "large capacity"	Incorporate in a single arc so single capacity constraint can be applied
Cataract to Macarthur	Pipe	200 ML/d if storage fraction < 0.45	Document basis of capacity
Broughtons Pass to Macarthur	Pipe	Unconstrained	Apply max capacity
Warragamba pipe to Warragamba demand	Pipe	Unconstrained	Apply max capacity
Warragamba pipe to Orchard Hills	Pipe	Unconstrained	Apply max capacity

### 6.1.5.2 Environmental flows and minimum releases

Environmental flow and minimum release settings are summarised in Table 6-6 along with review comments. Settings were checked against requirements in the 2023 Water Sharing Plan (WSP2023), noting that the 80<sup>th</sup> percentile flows for Tallowa and the Upper Nepean dams have recently changed. It was noted that some aspects of eflow settings for these dams matched WSP2023 and others did not. Those that did not include some aspects of the WSP requirements include Tallowa, Avon and Woronora as detailed in Table 6-6. It is recommended that updated flow recommendations be documented and checked against model settings. WaterNSW have advised that this has been reviewed and updated.

For Wingecarribee eflow and riparian releases it was noted from the model change log (Appendix B.1) that these higher costs were to overcome Wingecarribee carryover gains of up to 3000. It is recommended a specific rule be included to set aside the required water in storage instead.

A check was also made of flow versus capacity outputs from a single replicate run to see if the required flow was being passed. Results showed that Nepean Dam is not always releasing the full required flow, and time series plot shows this is due to a capacity constraint imposed by the total release arc downstream (660 ML/d).

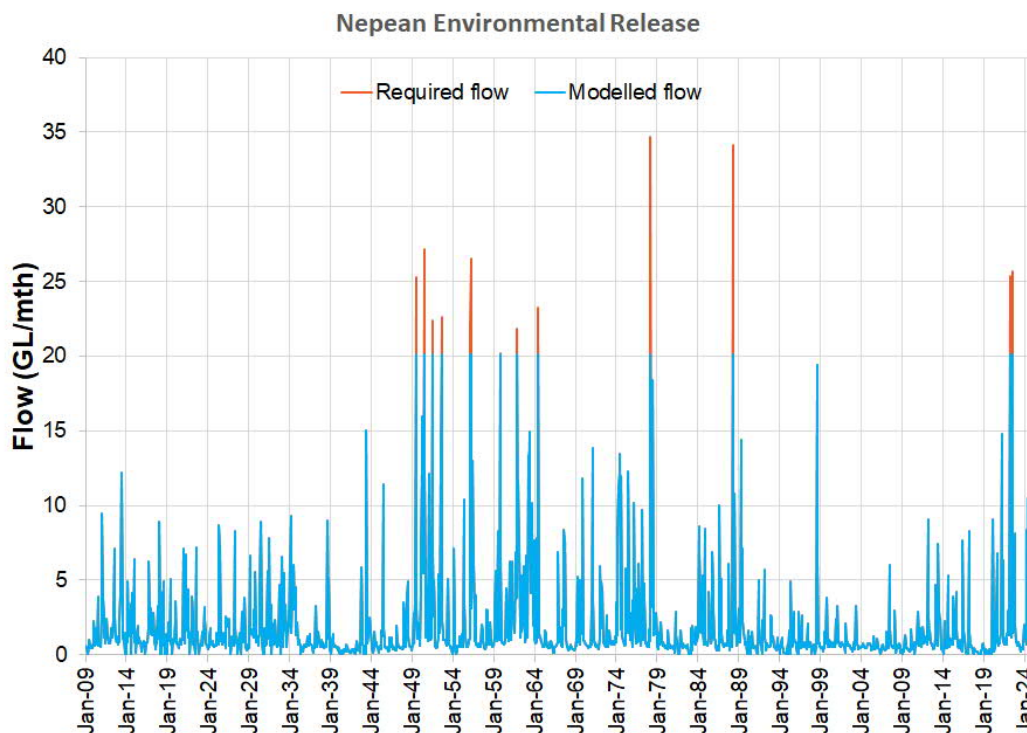


Figure 6-6: Nepean Dam environmental flow requirement and modelled flow

Arc costs are summarised in Appendix E of the review report. All other arcs were releasing the full required flow.

In the case of Woronora the high flow flag is switched off despite high flows being included in the WSP. WaterNSW advised that this has been reviewed and adopted.

In the case of the Macarthur eflow arc WaterNSW have advised this is not used and can be deleted.

**Recommendations (and their priority as high, medium, or low):**

- Updated passing flow recs (80<sup>th</sup> percentile values) for Tallowa and the Upper Nepean dams should be documented and checked against model settings (M)
- Use rules instead of higher negative costs to set aside water in Wingecarribee (M)
- Check performance of harvest node versus eflow equations under climate change (M)

Table 6-6: Environmental and minimum releases

Release from	Type	Rule	Review comments
Tallowa	Env & min	<u>Eflow</u> : Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (equation component) Eflow = [transparent flow (137-325 ML/d depending on month) + translucent flow (20% of inflw)]*scaling factor <u>Min flow</u> : 65 ML/d Total released capped at max release capacity of 750 ML/d. Cost -2000	As per WSP2023
Fitzroy Falls	Env	Eflow = 0.4* inflow. Cost -2000 <u>WATHNET notes on arc</u> FF Inflow = 4.4 times Wilds Meadow Inflow FF E-flow = 5/3 times Wildes Meadow Inflow FF E-flow = about 0.4 of Fitzroy Falls Inflow	As per WSP2023
Wingecarribee	Env	3 ML/d if above dead storage. Cost -3100	As per WSP2023. It was noted from model the change log that these higher costs were to overcome Wingecarribee carryover gains of up to 3000. It is recommended a specific rule be included instead.
Wingecarribee	Riparian	1 ML/d if above dead storage. Cost -3200	
Nepean	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (17.2 ML/d) + translucent flow (20% of inflw)]*scaling factor. Min release requirement of 2 ML/d set. Cost -2000	A check was made of flow versus capacity in a single replicate run and it showed that Nepean is not always releasing the required flow so the calculation should be checked and negative costs possibly increased.
Avon	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (9.4 ML/d) + translucent flow (20% of inflw)]*scaling factor if storage is > dead store. Min release requirement of zero set. Cost -2000	WSP2023 min requirement looks to be 1 ML/d. WaterNSW have advised that this has been corrected
Cordeaux	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (7.2 ML/d) + translucent flow (20% of inflw)]*scaling factor. Min release requirement of 1 ML/d set. Cost -2000	
Cataract	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (11.4 ML/d) + translucent flow (20% of inflw)]*scaling factor. Min release requirement of 1 ML/d set. Cost -2000	
Pheasants Nest	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (5.6 ML/d) + translucent flow (20% of local catchment inflw)]*scaling factor plus upstream eflow releases. Max capacity set of 3000 ML/d, min release requirement of 5 ML/d set. Cost -2000	
Broughtons Pass	Env	Eharvest option off. Scale option selected, scaling factor = TSS fraction Uses EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (1.8 ML/d) + translucent flow (20% of local catchment inflw)]*scaling factor plus upstream eflow releases. Max capacity set of 2000 ML/d, min release requirement of 1 ML/d set. Cost -2000	
Warragamba	Env & flushing	Warragamba e flow flag set to zero. Flushing flow of 5 ML/d released. Max capacity set of 3000 ML/d, min release requirement of zero set. Cost -2000 <u>WATHNET notes on arc</u> 90/10 scaled eflow proposed	
Woronora	Env	Eharvest option off. Halve option selected. Woronora high flow flag switched off. Use EFlowArcCalc subroutine (eqn component) Eflow = [transparent flow (1.2 ML/d) + translucent flow (20% of local catchment inflw)]*0.5 If Woronora > 20% then max release is 660 ML/d, else max release is 330 ML/d. Mn release requirement of zero set. Cost -2000	Storage fraction and 300 ML/d max release hard coded. Move to system table Woronora high flow requirements are included in WSP2023
Macarthur	Min	Turned off. Cost -4000	WaterNSW advised that this is not used and can be deleted

### 6.1.5.3 Restriction rules

In the start of replicate global script there is a subroutine *ReadRestnRegime* that sets the restriction regime to one of three options. Current setting is restriction option 1 that then reads storage triggers and savings levels from system table 15. Savings are converted to demand reduction in the subroutine. Notes in WATHNET say these are from the Greater Sydney Water Strategy, GSWS (2022).

The assumed percentage reduction in demand due to restrictions is linked to the expected savings arising from actions proposed at each restriction level. The basis of 7%, 12% and 19% values should be documented. The Expert Panel also suggested that a greater reduction in demand due to restrictions should be considered for the more severe restriction levels. Yield is run under an assumption of 3 levels of restrictions, while the scripting is set up to allow 5 levels of restrictions to be run if needed.

Table 6-7: Restriction regime for base yield settings from GSWS (2022)

Restriction Level	ON Trigger	Savings
Level 1	0.60 (g10)	7% (g11)
Level 2	0.45 (g12)	12% (g13)
Level 3	0.35 (g14)	19% (g15)

Total demand is made up of an unrestrictable portion (in-house use, commercial and industrial demands, etc) and a restrictable portion (out of house use). The WSAA Urban Water Resources Planning Framework (WSAA, 2024) recommends that savings be applied to restrictable rather than total demand, as this makes it easier to compare demand response throughout the year and across supply systems. Where demand reductions are expressed as a reduction in total demand, the seasonal variance in that demand reduction can be masked. For example, restrictions that generate a 10% reduction in annual demand are likely to result in a more than 10% reduction in drier months (when the outdoor water use would ordinarily be higher) and potentially no reduction in wetter months. Similarly, for equivalent restrictions in two nearby areas, but with vastly different proportions of unrestrictable industrial and commercial water use, those restrictions will not generate the same percentage reduction in total demand. It is recommended that this option explored.

The 'after timestep' global script calls subroutine *Cal\_Reliab\_Robust* (Calculate reliability and robustness). This subroutine calls the *getResLevel* subroutine which checks current total storage fraction against trigger levels and returns the relevant reduction in demand due to restrictions while also calculating instances of each restriction level. This value corresponds to global variable *restFrac* which is applied to each demand as described in Section 6.1.4.2.

From a reviewer's point of view, tracking the calculation of restrictions was difficult due to the number of nested subroutines and unnamed global variables. Opportunities to make this more transparent should be explored (refer Section 6.1.7).

The same storage fraction is used to turn restrictions on and off. As noted earlier, separate exit triggers could be considered for model stability, or to reflect operational practice. A time-based trigger could also be considered. (e.g. must be at a level for >1 month to change), with WaterNSW commenting that these were formerly in the model but are no longer policy.

Discussion of shifting trigger levels under yield modelling is included in Section 6.2.1.3.

It is noted that no reserve volume has been specified. As discussed in WSAA (2024) use of a reserve volume is a drought contingency measure that can be linked to lead time required for emergency response. Its use and size are a function of risk appetite and the desire to guard against climate uncertainty. It is recommended that use of a reserve storage be explored and the rationale for its adoption or otherwise documented.

**Recommendations (and their priority as high, medium, or low):**

- Document basis of reduction in demand due to restrictions (M)
- Consider a greater reduction in demand due to restrictions at higher levels (M)
- Explore the option of expressing savings as a proportion of restrictable demand (M)
- Explore the use of a reserve storage and document findings (M)
- Make restriction calculation more transparent (M)
- Consider exit triggers if appropriate (L)

#### 6.1.5.4 Extraction limits

The 2023 Water Sharing Plan sets Long Term Average Annual Extraction Limits for each extraction management unit. These are shown below.

Given these limits are part of the WSP it is recommended that they be tracked in the model and reported so that it can be understood whether they are being breached or not and if further investigation is required.

Table 6-8: Long Term Average Annual Extraction Limits (2023 Water Sharing Plan)

Extraction management unit	Long Term Average Annual Extraction Limit
Hawkesbury and Lower Nepean Rivers	6,000 ML/yr
Shoalhaven River	36,000 ML/yr
Southern Sydney Rivers	13,000 ML/yr
Upper Nepean and Upstream Warragamba	581,000 ML/yr

**Recommendations (and their priority as high, medium, or low):**

- Track Long Term Average Annual Extraction Limits in model so times when limits are exceeded can be reported and investigated (M)

#### 6.1.5.5 Water quality

The Expert Panel noted that Sydney Water raised concerns about the impact of source water quality on the ability to treat water. While WATHNET does not directly model water quality, the impact of these events can often be indirectly represented in water resources modelling using a proxy variable. For example, if water quality in a particular storage is poor below a certain level or at a particular time of year then operation below the required level or at that time of year can be constrained. Similarly,

shandying rules from different sources can be imposed. If the impact of more random events such as bushfire impacts or algal blooms need to be represented, the WATHNET harvest node could be used.

**Recommendations (and their priority as high, medium, or low):**

- It is recommended that the impact of poor water quality on bulk supply be considered, and if required, options to represent them with proxy variables be explored (M)

### 6.1.5.6 Representation of drought response

The Expert Panel suggested that the model be checked against the Greater Sydney Drought Response Plan (GSDRP) to review the adequacy of drought response measures built into the model. This would take the form of restriction trigger levels, percentage reduction in demand due to restrictions and operating rules. The Expert Panel noted that triggers for drought response listed in the GSDRP (e.g. rainfall, inflows, depletion time) do not align well with variables in the model which uses storage volume triggers. It was also noted that there were no specific measures for when storage is below 40%.

It is recommended that a check be made that the storage based triggers in the model produce behaviour consistent with that resulting from the more complex GSDRP indicators, acknowledging that alignment with the GSDRP is an ongoing consideration for WaterNSW into the future.

**Recommendations (and their priority as high, medium, or low):**

- check that storage based triggers produce behaviour consistent with that resulting from the more complex GSDRP indicators (M)

### 6.1.5.7 Water values

Some demands within the system can be supplied from more than one source, and there are interlinked storages. Where an explicit rule does not exist, the model needs settings to help it decide how total system storage at any given time should be distributed between individual storages. These should ideally be optimised to maximise system yield within system constraints.

Sharing of water between storages and storage drawdown is represented in the model using a technique referred to as Water Values. Gains (or penalties) on carryover arcs at each storage are manipulated to produce the desired storage behaviour.

There is an approach to deriving water values using a simplified model is described at a high level in SKM (2010). It is unclear whether this approach has since been refined by WaterNSW or if water values have been updated since that time. It is recommended that this be documented.

**Recommendations (and their priority as high, medium, or low):**

- Document the process of deriving water values and when/how current values were derived (M)

### 6.1.6 Overall model review - Model calibration and validation

Undertaking and documenting a model calibration and validation process is crucial to instil confidence in model results.

It is suggested that calibration be undertaken over the period for which a reliable historic streamflow, storage volume and demand data set is available capturing both wet and dry conditions (e.g. from 2000 onwards). As part of this process historic demands would be put into the model and historic releases and transfers forces (to get around any issues with changes in operating rules over time). Modelled volume in storage and flow at key locations can then be compared to recorded data.

A mismatch in storage traces would suggest mass balance has not been preserved and inflows and/or net evaporation require adjustment. A mismatch in river flows suggest the need to include or refine local catchment inflows and losses.

Once losses and mass balance have been checked via model calibration, the forcing of historic releases from storage can be removed and the operating rules in the model allowed to dictate the movement of water. This model validation should be done over a period for which current operating rules have applied, but again ideally over a period that captures both wet and dry conditions.

Mismatches in storage volumes or key transfers can be either used to refine operating rules, or where necessary explain why there is a difference (for example when a rule wasn't followed in practice for some reason). The calibration and validation process should be repeated periodically, particularly when the period of record has been extended or operating rules have been changed.

**Recommendations (and their priority as high, medium, or low):**

- Document the process of deriving water values and when/how current values were derived (L)
- Undertake model calibration and validation. Make adjustments to inputs and model settings and/or explain differences as required (H)

### 6.1.7 Overall model review – model setup practices

It can be seen from the previous review report and model scripts that a considerable amount of effort has been put into using global variables and common subroutines where possible, and using system tables as a single point of reference for key model assumptions. It is also evident that this is a work in progress. It is recommended that this work continues.

In particular, it would be useful if global variables were all assigned a meaningful symbolic name and this used in place of the g0x format wherever possible. It is also suggested that comments be added

to lines of scripts or at the top of scripts to explain the calculation being undertaken and the origin of any relationships (e.g. a report reference).

In terms of system tables, table notes should be included for all tables and address all rows and columns in each table. Table 16 is a good “grab bag” of key model settings. It was noted that there were a number of tables that contained multiple different setting types, for example Table 5 contains both storage characteristics and other data, it would be worth considering having sperate table for each separate setting type.

An overarching theme is the need for a single set of comprehensive and up to date documentation on the model inputs, settings and modelling approach. This could take a more traditional form such as a technical report that is regularly updated, or a more model centric form such as a set of “live” confluence pages that together explain the model. Documentation of this type could also incorporate details of different model runs and versions used for different purposes and their findings as an aid to version control.

**Recommendations (and their priority as high, medium, or low):**

- Continue working on implementing common subroutines and system tables (M)
- Assign meaningful names to global variables and use these in scripting (M)
- Add comments to scripts to explain the calculation being undertaken and its basis (M)
- Set up system tables for single setting types (M)
- Complete and maintain consolidated documentation of the model and model inputs. Consider approaches that allow for live updates and tracking of model runs and version control (H)

## 6.2 Review of yield modelling approach

This section documents the review of the current yield modelling approach as required by the project brief. Discussion of alternative modelling approaches and system performance measures other than yield is included in Section 6.2.4. and Section 6.3.

### 6.2.1 Run setup

The proposed model assumptions for 2026 yield modelling were provided by WaterNSW and are summarised in Table 6-9. Proposed assumptions discussed in more detail in the following sections, along with other aspects of run setup.

[Table 6-9: Yield model assumptions proposed by WaterNSW \(WATHNET Model Operating Licence Review - Design Criteria and Proposed Model Assumptions \(WaterNSW, 2025\) with minor modifications provided by WaterNSW\)](#)

Model Component	Assumption
<b>Hydrology</b>	
Historical Period	From 1909- 2024 (116 years)
Synthetic Hydrology	100 replicates (each 10,000 years)
Starting Storage	Replicate end storage carried over to start of replicate

Model Component	Assumption
<b>Climate Change</b>	
Climate Projection	NARClIM 2.0
Emissions Scenarios	: SSP2-4.5 (medium emissions) SSP3-7.0 (high emissions scenario) SSP1-2.6 (low emissions scenario) as a lower priority
Historical Baseline Reference Period	1996-2025 (centred on 2010)
Near Future Period	2040-2069 (centred on 2055)
Far Future Period	2070-2099 (centred on 2085)
<b>Demand &amp; Restrictions</b>	
L1 Storage Trigger	60% Aligned with Greater Sydney Drought Response Plan (GSDRP)
L2 Storage Trigger	45% Aligned with GSDRP
L3 Storage Trigger	35% Aligned with GSDRP
L1 Savings	4%
L2 Savings	10%
L3 Savings	18%
Demand Factors	Based on disaggregated climatic demand factors provided by SW for the period of 1909–2024.
Demand Distribution	Based on Run 81 nodal demand distribution
<b>Infrastructure Operating Rules</b>	
Shoalhaven ON/OFF	75% ON/ 80% OFF
Tallowa -3m Access Storage Trigger	Not included
Sydney Desalination Plant - Stage 1 Operation (Fulltime Flexible)	>90% 50ML/d; 75%-90% 125 ML/d; <75% 250 ML/d
<b>Environmental Flows</b>	
Environmental Flow Scaling	Environmental flow scaled on volume of water held in all Greater Sydney storages, expressed as a percentage of the total active storage capacity of all Greater Sydney storages
E-flow: Upper Nepean dams & Weirs	80/20 rule with scaling
E-flow: Woronora	80/20 rule. Additional annual High Flow Release 800ML/day over 3 days (subject to confirmation with DCCEE re: WSP proposal)
E-flow: Tallowa	Monthly Variable 80/20 rule with Scaling
E-flow: Wingecarribee Reservoir	3 ML/d (flows into Warragamba Dam)
E-flow: Fitzroy Falls	5/3 of inflow at Wildes Meadow (flows into Tallowa)
Riparian release: from Warragamba	17 ML/d in Winter and 25 ML/d in Summer for North Richmond WFP. 5 ML/d dilution flow for Wallacia WWTP
Riparian release: from Wingecarribee	1 ML/d
Riparian release: from Tallowa	65 ML/d for Shoalhaven City Council Supply

### 6.2.1.1 Start storage

For yield modelling, start storage is set in the first timestep of the simulation in the start of rep script as 90% of storage capacity. Storage capacities are listed in Table 6-10. For yield runs, storage at the start of each replicate is taken from the end storage of the previous replicate as specified in the before replicate global script. Given this approach setting initial storage, volume at the start of the simulation will have little impact on yield results. This approach is also adopted for end of replicate restriction levels. The start storage values specified in the before timestep global script are used for storage depletion runs and are not used for yield modelling.

Table 6-10: Current storage capacities used to calculate start storage for yield runs

Storage	Capacity (ML)
Warragamba	2,069,160
Woronora	72,657
Cataract	97,190
Cordeaux	93,790
Avon	213,450
Nepean	68,100
Wingecarribee	31,632
Fitzroy Falls	22,920
Tallowa	90,000
Prospect	48,220

### 6.2.1.2 Run length and number of replicates used

This model aspect was reviewed and commented on as part of the hydrology review (Section 3).

### 6.2.1.3 Demand and restriction settings

Storage levels to trigger restrictions in the current model correspond to the GSDRP based assumptions listed above. The savings under each restriction level for the yield analysis scenario have however been updated to align the savings adopted for the GSWS, (7%, 12% and 19% saving at Level 1, 2 and 3 respectively). Updated restriction saving values are provided by Sydney Water.

It is understood that demand factors in the model are updated values provided by Sydney Water. As detailed in Section 6.1.4.2, it is recommended that a check is made that the relationship between historic inflows/climate and historic seasonal fraction is maintained in the stochastic data. If not, it is recommended that a relationship as a function of climate be derived to determine climatic factors for use in synthetic runs.

The demand distribution currently in the model is based on Sydney Water's demand projection Run 70 from 2024 so needs to be updated. WaterNSW advised that this has been reviewed and updated. The process of yield modelling involves increasing demands until design criteria are just met. If for example demands in the system are 20% higher than they are currently, restriction triggers would be shifted accordingly to give the same lead time (i.e. the same duration of supply) between restriction levels. On this basis, it is recommended that for yield modelling restriction triggers be shifted in line with increases in demand.

#### 6.2.1.4 Operating rules

The Shoalhaven ON/OFF settings are included in the current model, implemented in the start of replicate script. Tallowa -3m Access Storage Trigger is not used.

The Sydney Desalination Plant - Stage 1 is switched to flexible full-time operation with the settings described.

#### 6.2.1.5 Environmental and minimum flows

All environmental and riparian flow settings in the current model correspond to the settings table with the exception of Woronora high flow (currently switched off) and Avon eflow (where minimum flow needs to be changed from 0 to 1 ML/d). WaterNSW advise that the Avon minimum flow has now been corrected.

#### 6.2.1.6 Convergence criteria and iteration failures

The linear program in WATHNET is subject to convergence settings. These settings are currently as follows:

- Number of iterations                      1 (min) 20 (max)
- Arc flow error                                5% or 2 ML is flow is less than 100 ML

WATHNET documentation recommends that the minimum number of iterations should be set to 2. It is recommended this change is made, which may also help with non-convergence.

Examination of the convergence report from a recent stochastic run shows that some arcs are subject to non-convergence, in particular pumping from Nepean to Avon but transfers into and out of Nepean more generally. It is recommended that the flows resulting from these non-convergences be examined for the single replicate case, and if they are unrealistic, then attempts should be made to improve performance of scripts, for example by altering evaluation times.

Table 6-11: Excerpt from convergence report from run 43 1909-2024

Convergence report:			
Average NLP iterations per time step =		3.492	
Report on Non-Convergent Arcs			
Arc	Name	% steps	Num steps
----	-----	-----	-----
51	Pumping Nepean to Avon	2.45	294328
107	Nepean Release for supply	1.25	150369
108	Nepean Tot Release (Supply + Eflow)	1.24	149393
16	Nepean Tunnel	0.94	112875
98	Cataract Supply Release	0.68	82087
99	Cataract Tot Release (supply+eflow)	0.68	81568
18	Glenquarie Cut	0.67	80909
101	Cordeaux Release for Supply	0.54	65191
102	Cordeaux Tot Release (supply+eflow)	0.54	64872
34	Winge-Warragamba SH transfer	0.52	62143
17	Upper Canal	0.32	38194
11	Warragamba Pipeline 3	0.21	24703
10	Warragamba Pipeline 2	0.2	23670
9	Warragamba Pipeline1	0.2	23629
95	Woronora to Sutherland	0.01	1045
3	Sutherland Supply from Prospect	0.01	1032
1	Supply from Woronora	0.01	1014

### 6.2.2 Assessment of outputs against design criteria

The Sydney water supply system is required to meet three Level of Service (LoS) design criteria which aim to limit the frequency and severity of restrictions and ensure a very low likelihood that the system will run out of water. The LoS criteria are provided to WaterNSW by the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW).

The current level of service design criteria are:

- Security: storages do not approach emptiness (defined as 5% of water in the storage) more often than 0.001% of the time, or one chance in 100,000 in any one month.
- Robustness: imposed water restrictions should not occur more often than once in every ten years on average.
- Reliability: imposed water restrictions should not last longer than 5% of the time on average, or 5 months in 100 months.

The WATHNET model includes scripts to track these values over the stochastic run. Results are output in such a way that they can be pasted into a template spreadsheet to provide a summary of run results.

Further discussion of level of service criteria informed by Expert Panel feedback is included in Section 6.2.4.4.

### 6.2.3 Uncertainty

The current yield modelling approach effectively relies on a 1,000,000 year stochastically generated sequence of inflows and climate inputs to determine yield that satisfies all the design criteria. If

system failure is for example dependent on the 1 in 100,000 (months) security criteria then yield will be being driven by only a few very dry climatic sequences within this data set.

To increase confidence in the yield figure it is recommended that several other data sets be stochastically generated using the same model parameters and the yield figure confirmed with these alternative data sets. The Expert Panel also suggested the stability of yield estimates could be investigated relative to the number of replicates analysed.

## 6.2.4 Yield modelling approach in context

System yield represents the maximum volume that the system can supply without breaching agreed level of service objectives. Water resources modelling can be undertaken for the purposes of determining yield or for other purposes (e.g. determining reliability, projecting system behaviour, augmentation planning, etc). Systems can be modelled in either in a steady or changing state.

These approaches are discussed below, paying particular attention to their use in determining system yield as this is the requirement of the current operating licence and the focus of this review.

Alternative measures of system performance are also discussed. Modelling approaches not directly related to determining yield are discussed in Section 7.

### 6.2.4.1 Stationary or steady-state modelling

WaterNSW currently employs stationary or steady-state modelling to determine yield, i.e. the model for a given supply system configuration is run with stationary model inputs (i.e. no underlying growth, climate change or other trends in climate, inflows, or demand). Under these conditions, demand is factored up until level of service objectives for reliability of supply are just met, in order to determine system yield. This is a common approach used throughout Australia.

This approach can be used to model non-stationary influences on supply system performance (e.g. climate change), but the stationary yield analysis must be repeated for each point in time over a planning horizon for which it needs to be known (e.g. climate change under a given emissions pathway in the year 2050, year 2070, etc.). This approach also has the advantage of being long established and accepted, primarily because the relationship between demand and yield over a planning horizon is visually powerful. An example supply demand curve is shown in Figure 6-7.

It is recognised that stationary modelling of yield is less accurate for systems with large storage and hence long storage memory that never effectively reach steady state, but that yield analysis is useful for visualising the gap between supply and demand.

### Example of a supply-demand balance under a range of climate and demand scenarios

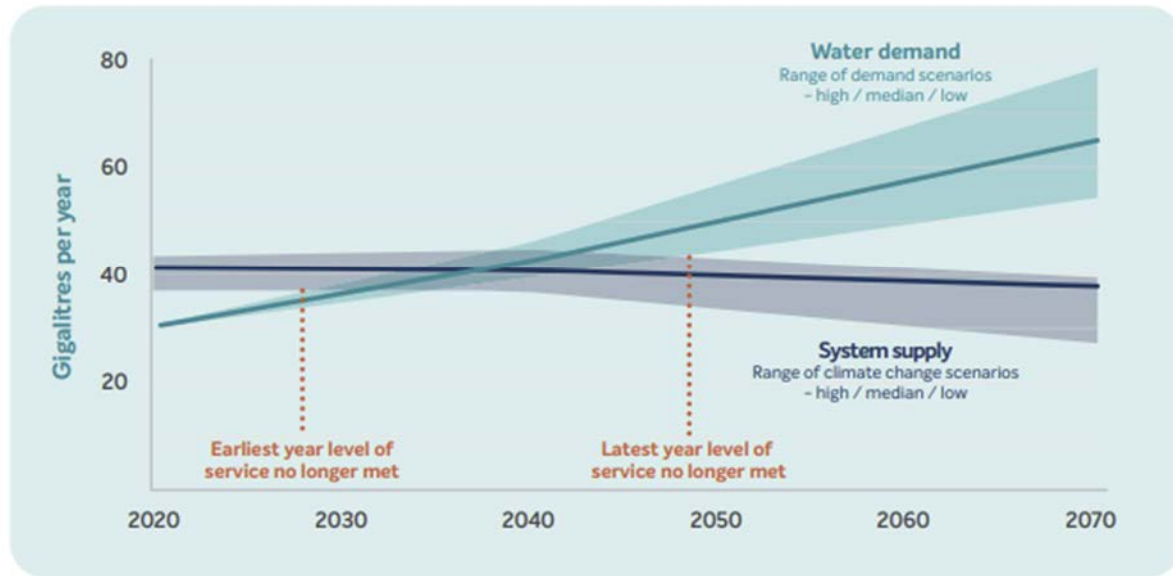


Figure 6-7: Example supply demand curve (Barwon Water 2022 Urban Water Strategy)

#### 6.2.4.2 Dynamic or transient state modelling

An alternative approach is to undertake dynamic (transient-state) modelling, as has been suggested in previous reviews. Typically, this approach projects system behaviour from current start storage conditions as a probabilistic outlook, with non-stationary inputs of a gradually growing demand and incremental impacts of climate change over time. The demand projections become an integral part of the water resource modelling. Planned system changes or augmentations can also be included. System behaviour in this case is heavily influenced by start storage. This approach has the advantage over stationary modelling of taking into account storage memory under changing conditions.

When dynamic modelling is undertaken, system performance against level of service criteria can be tracked over time, and the timing of failure to meet these criteria reported. Unlike steady state modelling it provides no information on the gap between supply and demand over time, instead only providing the point in time in future where level of service criteria will no longer be met.

It is noted that the WATHNET model is set up to be able to undertake both steady-state and transient-state modelling, but that the transient state parts of the model were not reviewed as part of this project.

To apply dynamic modelling in a yield assessment context, demands at each point in time could be increased so level of service is just met as other impacts such as climate change increase over time. This would be a more computationally intensive task than steady state yield assessment.

Under either a demand projection or a yield assessment application, transient state modelling introduces the issue of needing to assess level of service criteria across rather than along replicates. This is particularly an issue for the Greater Sydney system with the 1 in 100,000 security criteria which would necessitate the application significantly more than 100,000 replicates to get a statistically

defensible result in any given month over the planning horizon. It is difficult to predict exactly how many would be required across such a complex system, the easiest approach would be to carry out test runs, adding replicates until the results are stable.

The main advantage of transient modelling, as outlined in previous reviews and re-iterated by the Expert Panel, is that for supply systems with non-stationary inputs and many years of storage, the supply system never effectively reaches steady-state conditions. In the Greater Sydney supply system, if it is, for example, a decade between spill events in an extended drought, then the current volume in storage will have been affected by the demand and climate conditions that existed up to ten years ago, at both lower levels of demand and climate change. So, yield analysis undertaken under steady-state conditions, will slightly under-estimate the true yield if demand is increasing in a drying climate.

Transient modelling of system behaviour under projected demands also has the advantage that it does not pre-suppose a level of service objective. This enables changes in levels of service over time to readily be discussed. Where it has been adopted (e.g. in Melbourne), it has only been used for specific purposes (e.g. short-term storage outlooks of 1-3 years, or to support augmentation decision planning), and stationary yield analysis has been retained to enable more rapid estimates of supply system performance and to support public communication in water resource planning strategies with a planning horizon over many decades.

The Expert Panel noted that the significant influence of start storage on dynamic modelling results can be problematic for long lead-time water resource augmentation projects where the required timing of actions may vary wildly as a function of starting storage, which can become difficult to manage with stakeholders. This means modelling needs to be periodically updated (and the outputs communicated clearly) e.g. every 6 or 12 months. This is the case especially for making key decisions during periods with rapidly changing extreme climate behaviour such as when the system is experiencing very dry or very wet conditions.

The process of transient-state modelling and modelling results are also more complex to communicate to the general public and have generally been reserved for presentation to and discussion with educated stakeholders.

Pros and cons of each approach are summarised in Table 6-12 below.

Table 6-12: Comparison of modelling approaches

	Steady state modelling of yield	Transient state modelling of system behaviour under projected demands	Transient state modelling of yield
Can be run with existing stochastic data set (1,000,000 of replicates) and level of service criteria	✓	✗ more replicates would be required to reliably satisfy the 1 in 100,000 security criteria	✗ more replicates would be required to reliably satisfy the 1 in 100,000 security criteria
Better represents state of a system with large storages	✗	✓	✓
Provides information on the gap between supply and demand over time	✓	✗	✓
Required under current WaterNSW operating licence	✓	✗	✓
Provides outputs useful for a range of other purposes	✗	✓	✓
Results can be heavily influenced by start storage assumption	✗	✓	✓

### 6.2.4.3 Measures of system performance and their application

Determination of yield is useful for long term planning and is a requirement of WaterNSW's current operating licence. It is recommended that the current steady state approach to modelling yield is retained.

In the case of systems such as Sydney with large storage memory, yield is less useful for shorter term augmentation and drought response planning where system behaviour will be heavily influenced by start storage, with trends in climate and demand incrementally affecting water availability over time. For these applications dynamic modelling of system performance against level of service criteria is the more appropriate approach.

The Expert Panel also noted that adopting dynamic simulation may help to address some of the stakeholder feedback received from Treasury, for example:

- The question of 'should we invest now' for augmentation is just as important as long term planning based on portfolios of potential investments
- It's our understanding that WATHNET cannot directly estimate the risk of failure at any point in time, or the cumulative risk of failure year by year.
- What role does current storage level play in the analysis of Yield, and why? If not, how should current storage levels be used to assess water security risk?

While this review has been limited to determining the WATHNET model's suitability to calculate yield as required by the operating licence, it is prudent that the model be maintained to be able to undertake both steady state and dynamic modelling for different purposes. The Expert Panel noted that the model may need the following enhancements to be suitable for business case applications:

1. Scripts to track the evolution of performance metrics over the simulation period.

2. Scripts to track present worth operating costs and capital costs of interventions.

It is recommended that future reviews encompass both the steady state and dynamic aspects of the WATHNET model, and that performance measures other than yield be used for model applications not related to long term planning.

#### **6.2.4.4 Design criteria and operating licence conditions**

As noted above, the security design criteria with its extreme low likelihood can be problematic to assess effectively. Design criteria were discussed at the Expert Panel Workshop and in the Expert Panel feedback.

The security design criteria in particular was felt to not align with industry best practice. It is not consumer focussed and does not include consideration of the duration of an extreme dry event. It was also noted that this metric was developed before Sydney had its now sizable non-climate dependent sources of water. It was suggested an alternative metric could be considered that is linked to being able to supply a minimum viable supply (supply where sustainment of urban function and a minimum acceptable level of economic activity can just be maintained) for a chosen period of time or indefinitely.

The Expert Panel also suggested that a detailed study be done assessing aspects of the hydraulics and water quality characteristics for each of the reservoirs to define a realistic minimum operating level.

It was also suggested that the robustness and reliability design criteria could consider more than one restriction level given their different impacts on the community.

The Expert Panel recommended that the required functions of the model and associated system performance measures be reviewed as part of a broader review of operating licence requirements as the current operating licence constrains assessment of system performance to yield. While review of design criteria is outside the scope of this project, a recommendation is included here for future consideration by WaterNSW and stakeholders.

**Recommendations (and their priority as high, medium, or low):**

- Consider shifting triggers as demand increases under yield modelling (M)
- Make noted setting changes to demand distribution (if required) and eflows prior to 2026 yield modelling (H)
- Change minimum iteration setting to 2 (L)
- Investigate and if necessary improve arcs with non-convergences (M)
- Consider assessing uncertainty in yield using alternative stochastic data sets and/or by changing the number of replicates (M)
- Retain the current steady state yield modelling approach for long term planning
- Utilise dynamic modelling for shorter term augmentation and drought planning
- Include review of dynamic aspect of the model in future (M)
- WaterNSW and stakeholders to consider a review of the required functions of the model and associated system performance measures (M)

### 6.3 WATHNET review findings and recommendations

Recommendations made as part of the review of the WATHNET model and modelling approach are summarised in Table 6-15, Table 6-13 and Table 6-14. The classification of recommendations is as previously outlined in Section 6.1.

It was found that the current steady state approach to modelling yield is appropriate, subject to the completion of essential checks and corrections.

It was also found that the alternative (transient state) modelling approach is preferred to steady state modelling when assessing system performance of a system with large storage and non-stationarity inputs, and that steady state yield analysis does not answer all of the water resource planning questions posed by WaterNSW and stakeholders. This review serves as an opportunity for WaterNSW and stakeholders to explore the benefits of alternative modelling approaches, assumptions and applications to enhance outcomes in future.

Table 6-13: Summary of recommendations – Essential corrections / checks / enhancements

Model element	Recommendation	Priority	Level of effort	Refer to Section
Pipes etc	W1. Apply pipe/pump/canal/tunnel max capacity where they are not currently specified	H	L	6.1.5.1
Run setup	W2. Make noted setting changes to demand distribution prior to 2026 yield modelling	H	L	6.2.1.6
Run setup	W3. Make noted setting changes to eflows prior to 2026 yield modelling	H	L	6.2.1.6
2021 & 2025 rec	W4. Storage outlet capacity constraints - implement for Wingecarribee and Warragamba	M	L	6.1.1
Run setup	W5. Test and confirm value of adjusting minimum iteration setting to 2	L	L	6.2.1.6
Model calibration / validation	W6. Undertake and document model calibration and validation. W7. Make adjustments to inputs and model settings and/or explain differences as required"	H	H	6.1.6
Storages	W8. Check model and CMCR rating tables match	H	L	6.1.3.2
Inflows & climate	W9. Alter lake boundary adjustment if required based on recommendations in the HARC hydrology report	H	L	6.1.4.1
Inflows & climate	W10. Ensure net evap data set is consistent with that used for the CMCR water balance on storage calculation	H	L	6.1.4.1
Demands	W11. Check relationship between historic inflows/climate and historic seasonal fraction is maintained in the stochastic data. If required derive a relationship as a function of climate to determine climatic factors for use in synthetic runs.	H	M	6.1.4.2
2021 rec	W12. Shoalhaven transfer – recheck harvest node versus equation performance under climate change inflows	M	M	6.1.1.1
2021 rec	W13. Pheasants Nest and Broughton's Pass Environment Release - recheck performance under climate change inflows	M	M	6.1.1.1
2025 rec	W14. Demand shortfall arc incremental penalty – Demonstrate that the lower incremental penalty of 25,000 is sufficient to cause shortfall sharing or change to 100,000	M	L	6.1.1.2
2025 rec	W15. Nepean-Avon transfer rule – considered updated water values in conjunction with operator practices to come up with a new set of agreed rules	M	H	6.1.1.2
Layout	W16. Confirm that net local inflows and losses from transfers listed are negligible, and would remain so under climate change, otherwise explicitly represent these losses and net local inflows	M	M	6.1.3.1
Layout	W17. Check the need to represent demand zones and the transfer system in more detail	M	M	6.1.3.1
Transfers / triggers	W18. Make arc specific edits to key transfer infrastructure and associated operating rules as per Table 6-5	M	L	6.1.5.1
Transfers / triggers	W19. Justify tunnel daily to monthly conversion factor of 1	M	L	6.1.5.1
Transfers / triggers	W20. Justify canal daily to monthly conversion factor of 0.9	M	L	6.1.5.1
Enviro & min flows	W21. Check performance of harvest node versus eflow equations under climate change	M	M	6.1.5.2

Model element	Recommendation	Priority	Level of effort	Refer to Section
Restrictions	W22. Check that storage based triggers produce behaviour consistent with that resulting from the more complex GSDRP indicators (M)	M	L	6.1.5.6
Run setup	W23. Investigate and if necessary improve arcs with non-convergences	M	M	6.2.1.6
Model setup practices	W24. Complete and maintain consolidated documentation of the model and model inputs. W25. Consider approaches that allow for live updates and tracking of model runs and version control.	H	M	6.1.7
Storages	W26. Reconcile values in Prospect node, notes and system table 5	M	L	6.1.3.2
Inflows & climate	W27. Represent local inflows and the impacts of rainfall and evaporation on Prospect Reservoir to allow change under future climate	M	M	6.1.4.1

Table 6-14: Summary of recommendations – opportunities for improvement

Model element	Recommendation	Priority	Level of effort	Refer to Section
<b>Model improvement</b>				
Layout	W28. Confirm that the current and future impact of diversions and interception activities is negligible, or otherwise seek to quantify and document this influence on system inflows and transfers	L	L	6.1.3.1
Storages	W29. Resolve difference in Warragamba dead storage and capacity in node and system table	M	L	6.1.3.2
Storages	W30. Adopt dead storage at node wherever possible when the next version of WATHNET is released including adding representation of dead storage for Warragamba, Cataract, Cordeaux and Nepean	M	M	6.1.3.2
Storages	W31. Include explicit representation of active storage	L	L	6.1.3.2
Restrictions	W32. Make restriction calculation more transparent	M	L	6.1.5.3
Extraction limits	W33. Report on exceedance of Long Term Average Annual Extraction Limits in model	M	L	6.1.5.4
2025 rec	W34. Restriction policy script – Add subroutine to improve efficiency (L)	L	L	6.1.1.2
2025 rec	W35. Restriction policy script – Use global variable restlevel to help visualise restriction levels on plots	L	M	6.1.1.2
Transfers / triggers	W36. Avon to South Coast demand – Incorporate in a single arc so single capacity constraint can be applied	L	L	6.1.5.1
Demands	W37. Use getDemand subroutine for Goulburn and Bowral demand	M	L	6.1.4.2
Demands	W38. Test and if suitable calculate climate variable demand factors in model	M	M	6.1.4.2
Enviro & min flows	W39. Use rules instead of higher negative costs to set aside water in Wingecarribee	M	M	6.1.5.2

Model element	Recommendation	Priority	Level of effort	Refer to Section
2025 rec	W40. Unit Conversion Factor – Retain recommendation	L	M	6.1.1.2
Storages	W41. Represent Warragamba release to allow for drum gate in a separate arc	L	L	6.1.3.2
Water quality	W42. Consider the impact of poor water quality on bulk supply and if required explore options to represent them with proxy variables	M	M	6.1.5.5
<b>Model tidy up / defensibility</b>				
2025 rec	W43. Use robust naming convention – Retain recommendation	M	L	6.1.1.2
Transfers / triggers	W44. Check Woronora Dam to Sutherland arc is still required now demands all have 20 shortfall arcs	M	L	6.1.5.1
Model setup practices	W45. Continue working on implementing common subroutines and system tables	M	L	6.1.7
Model setup practices	W46. Assign meaningful names to global variables and use these in scripting	M	M	6.1.7
Model setup practices	W47. Add comments to scripts to explain each calculation being undertaken and its basis	M	M	6.1.7
Model setup practices	W48. Set up system tables for single setting types	M	M	6.1.7
2025 rec	W49. Invalid script settings – Continue to add as scripts are edited	L	L	6.1.1.2
2025 rec	W50. Echo Settings in a log file – Retain recommendation	L	M	6.1.1.2
2025 rec	W51. Use option dependent mapping – Retain recommendation	L	M	6.1.1.2
Storages	W52. Test and if suitable apply cost of 15,000,000 to all spill arcs	L	L	6.1.3.2
Transfers / triggers	W53. Remove commented out script if it will not be used in future	L	L	6.1.5.1
<b>Documentation recs</b>				
Enviro & min flows	W54. Updated flow recs for Tallowa and the Upper Nepean dams should be documented and checked against model settings	M	L	6.1.5.2
Transfers / triggers	W55. Justify or update cost settings	M	L	6.1.5.1
Inflows & climate	W56. Document inflows derived within the model using scripts (at weirs and St Marys)	M	L	6.1.4.1
Demands	W57. Include derivation of annual demands, demand zone disaggregation and seasonal factors in model documentation, including stochastic generation	M	M	6.1.4.2
Transfers / triggers	W58. Document basis of equations used	M	L	6.1.5.1
Restrictions	W59. Document basis of reduction in demand due to restrictions	M	L	6.1.5.3
Water values	W60. Document the process of deriving water values and when/how current values were derived	M	M	6.1.5.7
Layout	W61. Document the need or otherwise to represent hydro-electric transfers between Fitzroy Falls and Tallowa	L	L	6.1.3.1

Table 6-15: Summary of recommendations – Industry / modelling practice

Model element	Recommendation	Priority	Level of effort	Refer to Section
Yield modelling approach	W62. Retain the current steady state yield modelling approach	H	L	6.2.4
Dynamic modelling	W63. Utilise dynamic modelling for shorter term augmentation and drought planning	H	H	6.2.4
Dynamic modelling	W64. Include review of dynamic aspect of the model in future	M	M	6.2.4
Transfer network	W65. Consider representing the Sydney bulk transfer network to capture local constraints	M	H	6.1.3.1
Restrictions	W66. Explore the option of expressing savings as a proportion of restrictable demand	M	M	6.1.5.3
Restrictions	W67. Explore the use of a reserve storage and document findings	M	M	6.1.5.3
Restrictions	W68. Consider exit triggers, if appropriate	L	L	6.1.5.3
Restrictions	W69. Consider a greater reduction in demand due to restrictions at higher levels	M	M	6.1.5.3
Run setup	W70. Consider shifting triggers as demand increases under yield modelling	M	M	6.1.5.3
Uncertainty	W71. Consider assessing uncertainty in yield using alternative stochastic data sets and/or by changing the number of replicates	M	M	6.2.3
Design criteria	W72. WaterNSW and stakeholders to consider a review of design criteria	M	M	6.2.4.4

## 7. Broader Model Applications

Once built and calibrated, water resource models such as WATHNET can be used for a range of applications apart from yield modelling. Some examples are listed in Table 7-1.

Table 7-1: Example model applications

Modelling approach	Application	Comments
Short term stationary multi-replicate projection modelling	Use to forecast the likelihood of outcomes of interest (usually restrictions) over a short forecast period e.g. 12 months given current start storage	Provides risk-based information for key system management decisions
Stationary yield modelling at points in time over a given planning horizon with and without augmentations in place	When yield is compared against demand projections, the point in time when level of service objectives would no longer be met can be identified to support water resource planning decisions. Yield modelling can then be re-done at the required points in time to redraw the supply curve	Useful for high level planning of future system augmentation and demand management options
Dynamic modelling over a given planning horizon with growing demands and impacts of climate change	Estimates the likelihood of being in a given operating state (e.g. restriction level) at a given point in time. Can be used to assess risk (e.g. multi-year drought risk and multi-year desalination plant operating strategies) and as input to risk-based economic analysis, e.g. to support augmentation decision planning over the next 1-2 decades.	Useful for shorter term planning and staging of options Requires enough replicates to be able to reliably calculate system performance relative to current level of service objectives.
Optimisation of system operation	Optimise key model settings to maximise a particular outcome, for example supply equity or system yield	For an agreed system configuration, optimisation can help to refine operating rules.
Optimisation of augmentations	Optimise future interventions and associated operating rules for minimum cost	WATHNET multi-objective optimisation capability can be used to quickly find least cost solutions with satisfactory performance
Shock modelling	Test the system resilience to a particular shock, i.e. the loss of a particular supply source for a given period, e.g. due to a long-duration poor water quality event or asset damage	Can be used to ensure sufficient redundancy is in place if part of the supply system were to become unavailable.
Stationary and dynamic modelling to develop and test drought management options	Use short term modelling of “design” droughts and drought planning principles to determine restriction triggers and then test their performance under a wide range of climate variability with long term modelling	Can also be used to test the impact of various demand management options
Hydro-economic modelling	Include existing and potential new capital and operating costs along with restriction costs to stakeholders and the community to inform system augmentation planning and optimisation	Can be used for cost benefit analysis

## 8. Summary of Recommendations

Specific recommendations have been subjectively classified by HARC in the body of the report by their relative level of effort (low, medium, high) and prioritised (low, medium, high) based on their potential impact on model accuracy and/or estimates of yield. For the purposes of clarity and to support WaterNSW's implementation of the recommendations, the approximately 120 recommended actions described by HARC in the body of the report have been grouped into 33 categories. These are listed in Table 8-1.

Implementing the recommendations will improve the clarity and defensibility of WaterNSW's methods and in some cases could impact on yield estimates. Implementing these recommendations will ensure that WaterNSW addresses the WaterNSW Operating Licence 2024-2028 obligations regarding reporting, record keeping, and ease in providing information. This includes improved documentation of quality control checks, investigations, and model performance.

The priority for implementation of recommendations will be a matter for WaterNSW and its stakeholders. HARC has identified in Table 8-1 those individual recommendations considered in the review to be higher priority to correct an error or omission, to check whether an error or omission has occurred, or where the recommendation could have a material impact on supply system yield or the implementation of downstream tasks. Some recommendations, even if higher priority, are not low effort and may take some time (many months, not days or weeks) to test and confirm their suitability prior to adoption. Recommendations which are investigative in nature, or require collaboration with other stakeholders, may also take longer to implement than other recommendations. WaterNSW has reported to HARC that implementation of some of these recommendations has already occurred between the delivery of HARC's draft report and this final report, with those recommendations also highlighted in Table 8-1. The verification by HARC of actions implemented by WaterNSW since the issue of the draft report was not part of this review.

Table 8-1: Summary of recommendations grouped by theme. Suggested higher priority recommendations are highlighted in red. Recommendations already implemented by WaterNSW between the draft and final review report are highlighted in green.

Group number	Description	Individual recommendations (red = higher priority, green = already implemented by WaterNSW)
1	Develop and maintain documentation of input data and model development	H1, H2, H5, H6, H9, H10, H11, H12, H21, H22, CC14, CC20, CC22, <b>W24, W25</b> , W56, W57, W58, W59, W60, W61
2	Use gauged rainfall for deriving streamflow where possible unless gridded rainfall is the only available source of data and its use can be validated	H3, CC2
3	Undertake statistical testing for climate non-stationarity and non-climatic trends in hydroclimate data and appropriate de-trending for use in water resources modelling and climate change impact assessment	<b>H4, H8, CC1</b>
4	Investigate and adopt estimates of lake evaporation using Morton-based methods, with consideration of deep lake evaporation for reservoirs deeper than 30 m where found to be suitable	H7
5	Review and update historical inflow estimates where appropriate	<b>H13</b> , H14, <b>H18</b> , H23, H27

Group number	Description	Individual recommendations (red = higher priority, green = already implemented by WaterNSW)
6	Develop rainfall-runoff models that are calibrated using appropriate objective functions for water security assessment for historical inflow estimation and climate change impact assessment.	H15, H16, H17, H19, H20, CC4
7	Review stochastic data generation methodology	H24, H25, H26, H28, H29, H30, H31, H32
8	Develop framework for appropriate checks of climate model outputs and undertake those checks	CC7, CC12, CC13
9	Implement outlet and transfer capacity constraints within arcs, scripts and system tables	W1, W36
10	Reconcile Water Sharing Plan environmental flow release values and undertake check rules are up to date and incorporated correctly	W3, W4, W54
11	Undertake WATHNET Greater Sydney System model calibration & validation	W6, W7
12	Check and if necessary update representation of total and active storage in model	W8, W26, W29, W30, W31
13	Adopt consistent hydroclimate data sets and assumptions for inflow derivation, stochastic data generation, and for simulation	W9, W10
14	Check relationship between historic inflows/climate and historic seasonal fraction used for demand is maintained in the stochastic data. If required derive a relationship as a function of climate to determine climatic factors for use in synthetic runs.	W11
15	Check performance of harvest node versus proxy equations under climate change	W12, W13, W21
16	Confirm local inflows and losses do not need to be represented under either current or future climate	W16, W27
17	Revise calibration of water values and arc penalties for current base model conditions	W14, W15, W55
18	Improve representation of infrastructure and resolution of the representation of bulk water supply and distribution network to capture local constraints	W16, W17, W65
19	Confirm that the current and future impact of diversions and interception activities is negligible	W28
20	Model scripting updates to improve transparency	W32, W34, W35, W37, W40, W43, W45, W46, W47, W48, W50
21	Report on exceedance of respective Long-Term Average Annual Extraction Limits in model	W33
22	Consider alternative demand and restriction modelling approaches	W22, W38, W66, W68, W69, W70
23	Consider the impact of water quality on bulk supply and if required explore options to represent them with proxy variables	W42
24	Remove redundant scripts and arcs	W44, W53
25	Investigate, and if found to be suitable for the Greater Sydney region, undertake climate change projection and scaling methods using alternative approaches, including co variate analysis and pattern scaling	CC8, CC15, CC16, CC17, CC18, CC19
26	Investigate changing rainfall-runoff response due to extended drought or climate change	CC5, CC6
27	Consider utilising one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs	CC21

Group number	Description	Individual recommendations (red = higher priority, green = already implemented by WaterNSW)
<b>28</b>	Update demand distribution	<b>W2</b>
<b>29</b>	Make arc specific edits to key transfer infrastructure and associated operating rules	W18
<b>30</b>	Justify equations in documentation and scripts including daily to monthly conversion factors	W19, W20
<b>31</b>	Improve robustness of model and yield modelling process	<b>W5</b> , W23, W39, W41, W49, W51, W52, W71
<b>32</b>	Investigate alternative or revised design criteria, drought reserve policy concepts, and independent review scope	W64, W67, W72
<b>33</b>	A recommendation to retain and continue a business as usual activity	<b>CC3, CC9, CC10, CC11, W62, W63</b>

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## Appendix A Documents collected for the review

Table 9-1: Summary of documents collected for input to the review

Type	Description	Author	Date
Report / memo	WATHNET Water Supply Model Review 2026 Stakeholder Workshop – Tuesday 24 <sup>th</sup> February 2026 – NSW Treasury comments	NSW Treasury	Mar 2026
Report / memo	Feedback on WaterNSW Supply System Model Review	Sydney Water	Mar 2026
Report / memo	WATHNET Hydrology Update memo	WaterNSW	Feb 2026
Policy/ Regulatory Document	Greater Sydney Drought Response Plan Overview	Sydney Water and WaterNSW	Jan 2026
Report / memo	WaterNSW Rainfall-Runoff Model Development	WaterNSW	2026
Report / memo	Draft Framework for Selecting and Preparing Climate Change Data for hydrological modelling purposes	DCCEEW	2026
Report / memo	WATHNET Model Operating Licence Review - Design Criteria and Proposed Model Assumptions	WaterNSW	Oct 2025
Report / memo	Upper Nepean Toolkit Update	WaterNSW	Jun 2025
Report / memo	Climate Linked Demand Factors	WaterNSW	Mar 2025
Report / memo	Interim Model Review Report	George Kuczera	Mar 2025
Report / memo	Climate change adaptation position	Sydney Water	2025
Report / memo	eflow harvest node	WaterNSW	undated
Report / memo	Climate change adaptation guidebook	Sydney Water	2024
Report / memo	Annex A: Notes and logs of changes to the WATHNET model of Sydney System	WaterNSW	2024
Policy/ Regulatory Document	WaterNSW Operating Licence	IPART	2024
Report / memo	Assessing suitability of NARClIM1.5 and 2.0 for hydrological modelling	DCCEEW	2024
Policy/ Regulatory Document	Greater Sydney Water Sharing Plan	NSW govt	Jun 2023
Report / memo	Climate Change Impact Assessment for Greater Sydney Water Supply System	WaterNSW	Mar 2023
Report / memo	2021 Model Review Report	WREMA	2021
Report / memo	2016 Model Review Report	WREMA	2016
Report / memo	2010 Model Review Report	SKM	2010
Report / memo	CMCR description	WaterNSW	2006
Report / memo	2003 model review report	SKM	2003
Report / memo	1996 SMEC review	SMEC	1996
Report / memo	1991 SMEC review	SMEC & Sinclair Knight	1991

Table 9-2: Summary of technical data collected for input to the review

Type	Description	Provided by
spreadsheet	Log_WATHNET_ChangesFromDec2024_V1	WaterNSW
spreadsheet	WATHNET Model Yield Run QA & Mass Balance	WaterNSW
spreadsheet	Demand factors – far future, near future	Sydney Water
spreadsheet	NARClIM2 demand factors 20260122	Sydney Water
spreadsheet	CMCR spreadsheets	WaterNSW
spreadsheet	Historical period demand factors 20250224	Sydney Water
spreadsheets	Evaporation factors	WaterNSW
text files	HSPF inflows	WaterNSW
text files	Hist nodal inflows & climate	WaterNSW
*.wat	WATHNET files	WaterNSW
*.R	scripts for sampling stochastic data and converting net evap	WaterNSW
text files	Stochastic nodal data (inflows, climate)	WaterNSW
text files, csv files	Stochastic data generation outputs (diagnostics, etc)	WaterNSW



## Appendix B Stakeholder Workshop Minutes

## Minutes – WATHNET review stakeholder workshop

<b>Meeting</b>	<b>Project Briefing and Stakeholder Feedback Workshop</b>		
<b>Project</b>	WATHNET Model Independent Review 2026	<b>Project No.</b>	NSW00097
<b>Manager</b>	Stephanie Kermode	<b>Phone No.</b>	0411 966 554
<b>Location</b>	WaterNSW RM-PAR-L14.09-Training Room; Teams	<b>Date/Time</b>	24 February 2026 10:00 am – 12:00 pm
<b>Attendees</b>	DCCEEW – Mohammad Mortazavi-Naeini, Simon Williams, Rachel Watson Sydney Water – Paul De Sa, Jonathan Dixon, Lydia Aristuti, Marcia Dawson, Karen Chia IPART – Shweta Shrestha, Robert Aposhian WaterNSW – Allen Lal, Bede Johnston, Angelo Breda, Lorena Oliveira, Michelle Zhang HARC – Kate Austin, Stephanie (Steph) Kermode, Phillip Jordan, Brad Neal Wingecarribee Shire Council – Om Malla, Graeme Mellor, Clinton McAlister Sydney Desal – Matt Blaikie, Iftekhar Omar Goulburn Mulwaree Council – Marina Hollands, Trevor Sultana NSW Treasury – Peter Leventis, Sarah Wong, Rassam Moshrefi Shoalhaven City Council – DJ Dubose Total Environment Centre – Saul Deane Melbourne Water – Tim Hatt, KS Tan, Udaya Kularathna		
<b>Apologies</b>	David Gough, Helen Keenan, Lydia Aristuri, Robert Aposhian, Rassam Moshrefi		
<b>Distribution</b>	As above		

HARC was commissioned by WaterNSW to conduct an independent review of the Greater Sydney WATHNET model in accordance with its Operating Licence. This element of the review process supported the stakeholder consultation requirement through a briefing package and workshop. In conjunction with the attached slides, these minutes reflect the discussions at the stakeholder workshop.

Item
<p><b>1) Introduction &amp; context for the independent review</b></p> <p>Bede Johnston (WaterNSW Infrastructure Capability &amp; Risk Modelling Manager) provided an introduction describing the purpose of the review.</p> <p>WATHNET is the water supply simulation model used by WaterNSW to calculate sustainable yield in accordance with the design criteria for the Greater Sydney system. It informs regulation and investment decisions made by the NSW Government.</p> <p>The independent review is required under the WaterNSW Operating Licence to:</p> <ul style="list-style-type: none"> <li>■ Confirm modelling approaches reflect industry best practice.</li> <li>■ Identify opportunities for improvements.</li> <li>■ Consider feedback from stakeholders</li> <li>■ Submit a final report by 30 June 2026.</li> </ul> <p>It was reiterated that the scope of the workshop was focused on these requirements and did not extend to discussions around appropriateness or review of level of service objectives and noted that these are being considered in a parallel process.</p>

Item

**2) Introductions**

Agency representatives introduced delegates in attendance and outlined their roles and interest in the process.

It was noted that multiple agencies are participating in this review process for the first time and the deeper understanding of the modelling and its use would be beneficial.

Aspirations related to the WATHNET model, yield calculations and water security outside of the WaterNSW requirements were expressed by multiple stakeholders. Although out of scope for this workshop and process, it was confirmed that these could be noted in the report.

**3) Summary of recent WATHNET model developments – Allen Lal**

The historical development and context for the WATHNET model was described, with a brief overview provided of its development and major reviews undertaken since the initial model build in 1996. Further detail was provided on the findings of the most recent major review in 2021. Key recommendations resulting from that review were outlined and included actions to:

- Investigate local supply failures.
- Improve how the outlet capacities of dams are modelled.
- Improve representation of daily to monthly pumping and release volumes.
- Recalibrate of water values (drawdown curves).

A summary of developments since the 2021 Review was outlined, including:

- 2022 – Incorporation of the Greater Sydney Water Strategy reliability criteria and desalination operating rules
- 2023 – Adoption of the NARCLIM 1.5 Climate Change Impact Assessment.
- 2023 – Incorporation of Water Sharing Plan updates to reflect current regulatory requirements, including implementation of scaled e-flows for the Upper Nepean dams and Talowla Dam.
- 2024 – Updates to hydrology
- 2026 – Work to incorporate NARCLIM 2.0 Climate Change Assessment into the modelling to support new Operating Licence requirements.

Following this overview, Steph noted to the group that in addition to the major reviews outlined, a number of minor reviews had occurred, on an as required basis. Each of the major and minor reviews found the model to be fit-for-purpose in supporting decision making. The recommendations reflected incremental improvements to better reflect changing regulatory and operational practices, as well as adoption of the advancing capabilities of modelling software and practice that have progressed over the past three decades.

**4) Project scope and timeframes – Steph Kermode**

Steph Kermode (SK) of HARC provided an overview of their role and scope of engagement for undertaking the yield review, with HARC's role encompassing critical review of the WATHNET Model, changes in input data and modelling methods, the input data, key assumptions and methodology used by WaterNSW in the determination of system yield, as well as the impacts of climate change. Additionally, reasonable consideration of feedback of relevant stakeholders that have an interest in the determination of system yield forms part of HARC's scope.

SK explained updates to the model undertaken as part of the review process will be contingent on the findings of the review, agreement with WaterNSW on the suggested changes and their prioritisation, and time available for implementation. Where constraints prevent updates within this project scope, suggestions will instead be captured as recommendations for future enhancement in the report.

Key dates for stakeholder awareness were outlined and noted here:

- Preliminary report on findings of the review – 6 April 2026
- Expert Panel Workshop – mid-April 2026
- Draft Final Report – 1 June 2026

**Item**

- Final Report & Project Completion – 30 June 2026 (Operating Licence requirement)

Following HARC's overview, there were follow-up questions and discussion from multiple stakeholders regarding what was in and out of scope for this project.

It was clarified that in scope items include reviewing the WATHNET model, assumptions, input data, implementation, calibration and validation (rules, etc.), as well as reviewing the way in which it is applied to determine yield.

SK reiterated that the application of WATHNET for other purposes (e.g. multi replicate outlook runs starting from current initial conditions to provide probabilistic outputs over forecast periods of ~1–10 years), level or service and the impact of water quality on water security is out of scope, but in response to stakeholder queries HARC will comment on the models suitability for these applications in the report.

Paul De Sa (SW) asked who was on the expert panel. It was confirmed that a short list had been compiled but availability was still being determined. The project team committed to informing stakeholders once this had been confirmed.

Actions:

- WaterNSW to notify stakeholders of expert panel members, once confirmed
- HARC to capture out of scope items in the final report

**5) Questions for stakeholders to reflect on – Steph Kermode**

To frame questions and discussions arising from the following technical discussions, questions for consideration were posed to the stakeholder group, with reference to the scope of this review. The questions presented were:

- Is the model providing the information required?
- Is the representation of the system appropriate?
- What is important for reporting climate change impacts?
- Are there additional references that HARC should consider?

**6) Melbourne Water presentation – Tim Hatt, KS Tan, Udaya Kularathna**

Melbourne Water (MW) were invited to present on their water resource modelling experience and yield modelling as a utility with similar regulatory obligations.

The presentation focused on climate change considerations, different modelling approaches used for different purposes, and findings.

Melbourne Water current approaches to Water Resource System Planning seek to assess:

- Impacts due to climate change and demand level at future points in time
- Impacts due to progressively occurring climate change and demand growth over time

Key technical considerations in MW's approach to modelling presented to the group include:

- Melbourne Water does not currently need to translate climate model outputs to it's catchments
- Work is ongoing to investigate / represent the non-stationarity in stream flows due to bushfires and increasing temperature in stochastic data sets.
- While 120 years of record is available, analysis has identified a decline in rainfall captured of over 100 GL/a since the Millenium drought. The yield value produced by Melbourne Water was noted to be a median of 113 cycled replicates.
- Melbourne Water use water outlook zones in their catchments, and triggers for response are linked to decline total system storage at these points. These zones are reviewed every 5 years, and these reviews have shown a consistent trend across the catchments of shortening response times (i.e. that we need to act earlier).
- Currently, there is a need to actively respond when the total system storage reaches 75% capacity. In seeking to understand the impact of climate change on yield for long term planning, multiple

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climate change scenarios are assessed, with the same modelling assumptions to provide point-in-time assessments.

- The timeframes are at ~present, 2040 and 2065
- supply-demand gap is estimated based on point in time yield and demand projections.

The MW presenters noted the following observations and experiences on modelling water security in their context:

- Yield is the maximum static demand that can be supplied without breaching level of service criteria, which are reviewed every five years (i.e. the same as the WaterNSW requirement).
- Yield as an approach is long-term planning indicative, and not suitable for triggering augmentation, although some model outputs remain informative.
- Yield modelling can be applied to examine long term system capacity, and support water resources strategies.
- Advantages of this approach include simple visual communication, less data processing, a statewide standard, the ability to include progressive climate change, and scenario analysis.
- Disadvantages include uncertainty over augmentation decisions and timing, the absence of risk or probability analysis and reliance on pre-defined level of service.
- In contrast, using a dynamic or non-stationary modelling approach can better articulate system behaviour and responses. These projected system behaviour modelling approaches using a stochastic data set are able to be applied to short-to-medium term system performance analysis, operational and infrastructure planning (including augmentation), and economic and risk analysis.
- Advantages of this approach include dynamic simulations and scenario analysis capability, analysis of multiple metrics, robust analysis of possible futures and risk analysis capability.
- Disadvantages are that the approach is data intensive for both inputs and outputs, complex and time consuming to build and run, and the communication of complex results can be challenging, particularly compared to a single number output like yield.

Examples of MW's applications of respective approaches was provided to summarise their utility -MW use steady-state modelling of yield for long-term planning but use transient-state modelling for desalination water ordering and augmentation decision planning.

Mohammad Mortazavi (DCCEEW)– Queried how MW determine enduring supply volumes and augmentation lead times, and how the modelling outputs support these. This question was taken on notice by HARC and MW.

**7) Topic area: Hydrology – Phillip Jordan**

Phillip Jordan (PJ) of HARC provided an overview of the hydrology considerations in developing the WATHNET Stochastic model and component under consideration by HARC as part of the review.

It was noted that areas under review included:

- Historical inflow, evaporation and rainfall datasets used in the WATHNET model, incorporating proposed changes to methodology to develop historical input data for stochastic generation, and recommendations on the suitability of the datasets for yield estimation. For historical data, rainfall gauging and data, streamflow gauging, rainfall-runoff models, evaporation and evapotranspiration inputs and their veracity are all examined.
- In addition to treatment of the data, requirement and process for removal of non-climate related trends introduced as artefacts of unrelated process or occurrences.
- Suitability of stochastic data generation and approaches, as well as duration and number of replicates
- Mass balance approaches and adjustments – noting that WaterNSW utilises a process/tool titled CMCR to undertake its mass balancing to derive inflows informing WATHNET Stochastic generation.

Additionally, PJ provided an overview and explanation of the following to the group:

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- Stochastic data generation is also necessary as the instrumental record is too short to produce robust level of service or design criteria results – and hence robust yield assessments (116 years of rainfall data ~ 1,400 months). The design criteria requirement that the probability of total system storage dropping below 5% for 1 in 100,000 months can only be assessed via use of stochastic data. The use of a longer-term record also enables the potential to capture climate variability for the region.
- Annual or seasonal inflows are generated from a probability distribution fitted to observed data and incorporating cross-correlations and used to assess system performance against criteria. PJ showed Graphs to demonstrate how the use of stochastic data provides more complete curves and characteristics to inform understanding of system behaviour and responses.
- Annual inflows to Warragamba, Shoalhaven and Avon are all positively correlated with each other, and this correlation is accommodated by the stochastic data generation method within the WATHNET model.
- The way the CMCR adjustments work however, both with historical data and within the WATHNET model (for modelling current, future and stochastic conditions), was noted in the session as difficult to understand and audit.

PJ reiterated that output from this component of the review will include a review memo to document findings for consideration by WaterNSW and the Expert Panel, as well as any proposed updates and associated advantages and disadvantages of any alternate method(s) suggested.

**8) Topic area: The WATHNET model – Kate Austin**

Kate Austin (KA) of HARC provided an outline of the WATHNET Model review component of the process, noting the independent review of the WATHNET model has two broad parts:

- Part A – Review of model setup and application for yield modelling.
- Part B – Recommend revisions where appropriate, and if agreed, update the model and re-calculate the system yield.

Aspects considered under Part A include:

- Model inputs (inflows, climate inputs, demands)
- Physical system
- Representation of operating rules
- Model validation
- Model application to determine yield

KA noted that review will have a particular focus on recommendations from the 2021 model review, and the 2024 interim review.

The output from Part A will include a review memo to document findings for consideration by WaterNSW and the Expert Panel.

The approach to Part B includes the following:

- Recommendations for model enhancement for WaterNSW consideration.
- A Review memo, to be provided to Expert Panel for comment and consideration of their findings.
- Priority updates recommended to WaterNSW.
- WATHNET model updates where agreed.
- Yield modelling undertaken with updated model.

KA summarised the output from Part B includes:

- Updated WATHNET model and yield assessment.
- Documentation of the model, model updates and yield modelling including recommendations for future enhancement.

**9) Topic area: Climate change – Brad Neal**

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Brad Neal (BN) of HARC provided the overview for the review of climate change incorporation into yield modelling by WaterNSW, with the scope including:

- Review of the climate change impact methodology adopted to determine the impact to system yield, including any implications for water security analysis because of assumptions adopted for the method.
- Proposing of refinements or alternative approaches in consultation with WaterNSW, and (if implemented)
- Determination of the resulting climate impacted yield.
- Finally, it will advise on the suitability of the climate affected yield estimates for water supply planning, including considerations for limitations and uncertainty.

BN outlined that the review will examine the WaterNSW (2023) Climate Change Impact Assessment for Greater Sydney Water Supply System using NARClIM1.5 data. File notes from WaterNSW on updated methods associated with NARClIM2.0 work in progress will be reviewed as they become available during the project.

BN outlined key technical considerations for the review, including:

- Model bias correction methods
- Climate reference periods
- Rainfall-runoff modelling used to support the climate change impact assessment
- Historical data stationarity in the context of climate change
- Drought persistence in the context of climate change
- Stochastic data generation approach in the context of climate change
- Potential implications for water security risk assessment of the methods adopted for the above aspects

BN also noted the following additional context that HARC is aware of that are relevant to the review:

- NARClIM2.0 has been released and adopted as a Common Planning Assumption by the NSW government
- NSW DCCEEW has been developing guidance on hydrologic data preparation and climate change impact assessment (general framework, and technical guidance for metro water planning)
- NSW Regional Water Strategies paleoclimate datasets have been adopted as a Common Planning Assumption
- A number of climate change impact assessment methods for water resource analysis around Australia have been published since 2023, each using different analysis methods tailored to the application
- Recent innovations present incremental improvement opportunities that did not previously exist

The output from this component of the review will include a review memo to document findings for consideration by WaterNSW and the Expert Panel, as well as any proposed updates and associated advantages and disadvantages of any alternate method(s) suggested.

Following this overview, the following Discussion items were raised:

Marcia Dawson (SW): What about the Sydney Water interface for climate change impact assessment? Sydney Water have a different position on climate change adaptation, and subsequently corporate climate change assumptions. It was agreed that further understanding of SW's documented position and policies related to climate change would benefit the review.

PDS (SW) – Can water quality triggers be modelled?

KA (HARC) noted that water quality can be considered in water resources models if a proxy can be used as a trigger (e.g. storage level, time of year, months since inflow, etc)

Bede Johnston (WNSW) noted that WNSW had a water quality modelling project underway in parallel, but water quality was not currently incorporated into WATHNET modelling due to the myriad of

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<p>management options and uncertainties regarding water quality prediction and associated operational responses.</p> <p>Karen Chai (SW) – It is really important that we understand water quality as well, as we need to use SDP when the storage is full if water quality is bad, as notably occurred in 2020.</p> <p>SK (HARC) noted operational or incident management arrangement out of scope for this review, however suggested HARC could note this relationship in the report for consideration of future modelling approaches</p> <p>Action:</p> <ul style="list-style-type: none"> <li>■ HARC to request documents outlining Sydney Water’s climate change position and demand modelling assumptions under projected climate change</li> </ul>
<p><b>10) Lunch</b></p>
<p><b>11) Recap and introduce afternoon session – Steph Kermode</b></p>
<p><b>12) Group discussion</b></p> <p>The purpose of this session was to provide time for stakeholders to raise questions regarding the model and its outputs (including yield), the approach to the independent review, and any related issues not yet captured. Key points raised in the discussion are summarised below.</p> <p><b>Yield, water security and communicating uncertainty</b> – Stakeholders noted that yield should be contextualised within the broader water security landscape and does not, on its own, describe water security (including where water quality can affect security outcomes). It was also noted that yield is typically communicated as a single number, and stakeholders queried how uncertainty or a range could be communicated (noting the Melbourne Water example of presenting multiple points on a curve).</p> <p>In response, it was noted that the separate processes are examining related considerations around yield criteria, water security and level of service.</p> <p><b>Sydney Desalination Plant (SDP) and Blue Mountains representation</b> – Stakeholders asked whether SDP operating rules were included; it was confirmed they were explicitly represented in the WATHNET model as a full-time flexible rule. Stakeholders also sought clarification on how yield interacted with the Blue Mountains system; it was outlined that upper Blue Mountains demand was small relative to Greater Sydney demand and was excluded from the Greater Sydney model for computational efficiency, while lower Blue Mountains demand was represented within Orchard Hills demand and design criteria obligations. It was also noted that WaterNSW maintained a separate WATHNET model for the Blue Mountains/Fish River Water Supply Scheme.</p> <p><b>Broader uses of WATHNET and communication</b> – Stakeholders noted that WATHNET had uses beyond the yield assessment and that these were not widely understood. It was noted that, while HARC’s scope was defined by the Operating Licence requirements, the report provided an opportunity to record gaps/concerns, provide context on parallel processes, and note issues raised that were outside the workshop scope.</p> <p><b>Additional modelling outputs, stochastic generation, and reference materials</b> – Stakeholders queried whether review considerations could extend to additional outputs and technical settings that can be derived from WATHNET (e.g., probability curves/by-products, the number of replicates required for level of service assessment, and thinning procedures), and how modelling could support understanding of drought management and uncertainty (including reference to published work on yield uncertainty). Stakeholders also noted that draft climate change guidance nearing finalisation was expected to be used as a reference for future modelling approaches and assumptions. A question was raised regarding the stochastic data generation approach (rainfall versus streamflow). It was noted that these matters were outside the scope defined by WaterNSW’s Operating Licence obligations; however, HARC noted these points would be captured for context and follow-up discussions (including a proposed meeting with DCCEE) would assist in accurately reflecting the issues raised.</p> <p><b>Desalination planning and forecasting limitations</b> – Stakeholders raised the need for information to support medium-to-long term planning for desalination operations, including understanding production requirements, reliability of outputs, and inputs to regulatory and budgeting processes (including a five-year forward view for desalination volumes). It was noted that hydroclimate forecasting for Greater Sydney was challenging and there was broad agreement that desalination requirements could not be</p>

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accurately predicted over a five-year period or longer. The distinction between statistical outputs from models such as WATHNET and forecasting was noted, and it was suggested that further discussion was required on what information could be provided and the associated processes and relationships.

**Local system impacts (Shoalhaven / Tallowa Dam)** – Shoalhaven City Council raised local supply considerations relating to Tallowa Dam operating levels and impacts on supply to Kangaroo Valley and Nowra, and sought information relevant to drought planning (including how Sydney’s 23 GL allocation might be drawn down during drought). It was suggested that a separate discussion between WaterNSW and Shoalhaven City Council would be held to walk through the model and determine what information could be provided.

**Local impacts and policy settings** – Stakeholders queried what the modelling indicated about local system impacts (e.g., where constraints might be expected to arise first) and how readily policy settings could be tested in the model (for example, changing the storage threshold used for a security criterion). It was noted that recent changes to the Upper Nepean operating rules were intended to address consistency in modelled low level shortfalls below 5% storage.

**Decision-making needs and consultation on inputs** – Stakeholders emphasised the importance of transparent reporting that supported decision-makers’ understanding of yield and water security considerations. NSW Treasury noted the need for modelling insights that could inform the timing of augmentation and other near-term investment decisions; it was noted that these decisions were not the purpose of the yield model and were outside the scope of the Operating Licence review but would be recorded for context. Sydney Water also sought confirmation that it would be consulted regarding the inputs it provided to the model.

Actions:

- WaterNSW to arrange discussion with Shoalhaven City Council
- HARC to arrange meeting with Sydney Water to discuss model inputs
- HARC to arrange meeting with Mohammad to capture the points raised
- HARC to request slides from Melbourne Water
- Broader model use and context to be noted in report
- HARC to reflect concerns raised that were out of scope in the final report for context

### **Questions submitted via Team Meeting Chat Box:**

#### **Peter Leventis (NSW Treasury)**

- Melbourne Water’s point about taking decision makers on journey is paramount. A final report that can do this with this review or required yield report may help. Transparency and easy of understanding is helpful.
- On climate change assumptions, Treasury considers common planning assumptions should be the primary source which can be tested with other information. But this is crucial for investment decisions.

#### **Mohammad Mortizavi (DCCEEW)**

- How much integrating demand related data (i.e restrictions savings as a percentage or time series, demand factors) impacts on the yield estimation? Is there any improvements in terms of integrating demand side for WATHNET?

### **13) Process from here – Steph Kermode**

SK provided an overview of the process and next steps post-workshop. SK outlined that reviews and reporting components had commenced, and that the minutes and slides from the workshop would be distributed.

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<p>A large amount of information was delivered and discussed during the meeting, and any follow-up clarifications or comments were encouraged to be sent on for consideration.</p> <p>Action:</p> <ul style="list-style-type: none"><li>• Provide any remaining comments for consideration to <a href="mailto:wathnetreview2026@waternsw.com.au">wathnetreview2026@waternsw.com.au</a> by Friday 6 March.</li></ul>
<b>15) Close</b>



## Appendix C Stakeholder Written Feedback

## **Sydney Water feedback on WaterNSW Supply System Model Review**

It was noted in the workshop that this project aims to provide an independent review of WaterNSW's water supply system model, currently WATHNET, focused on its suitability and capability to estimate Greater Sydney's system yield as per WaterNSW's Operating Licence.

Given stakeholder and public visibility of the final review report and the associated updated yield value, it is important for the report to clearly articulate the broader purpose of the supply system model in assessing, monitoring and informing decisions to manage Greater Sydney's water security.

The report should also recognise the limitations of yield in understanding and defining water security risks and the role of other supply model outputs and measures. Such limitations should include at a minimum:

- Exclusion of raw water quality and/or treatability limits in the yield value from the water supply model both now and in the future. For example, we have seen changes in the quality of raw water within Warragamba over the last 20 years. This was first noted following the end of the Millennium Drought, however the water quality in the dam has not returned to pre-drought conditions.
- It does not capture short to medium term events. For example:
  - poor raw water quality following bushfires and flood events. Drought conditions, bushfires and flooding resulting in poor raw water quality in Warragamba Dam between 2019 and 2023. The Sydney Desalination Plant was operated over this period to manage water quality by reducing the use of poor quality water from the dams.
  - the uncertain quality of water within the dams when they fall below historical lows.eg. below 30%.
  - uncertainty in water distribution system hydraulics to enable the supply water across the entire Sydney Water network when dam levels fall below historical lows.eg. below 30%
- Note that yield should not be used alone for the purpose of planning and scheduling investment decisions. Other water supply model outputs combined with data from other sources can contribute for these purposes.

Without recognising limitations like these, the current water security risk in Greater Sydney may be understated or not well understood.

Part of this review process is also reviewing the assumptions used in the calculation of yield. There is a need to be clear about all assumptions informing this yield update and confirm if it will capture:

- The yield for the Blue Mountains, and therefore onset of drought to the system
- The impact of Blue Mountains storages being offline
- Any changes to the operational rules of DWPS
- Current operating rule settings.eg. full time flexible operation of Sydney Desalination Plant and Water Sharing Plans

In terms of the water supply model, it would be beneficial for:

- Outputs to include the contribution of individual rainfall independent supplies (RFIS) to yield to understand the expected utilisation of these assets over the long term and inform planning of new RFIS.
- Clear definitions and labelling of the different values of yield contribution and production values from different sources where applicable. I.e. Sydney Desalination Plant production vs contribution to yield.
- Adding more replicates to help with the assessment of low likelihood events .ie. rare occurrences of low inflow; and consider identification of P50, P90 replicates for particular timeframes.
- Consideration of raw water quality; or at least approaches that could be used to capture water quality impacts, in the quantification of yield and other supply model outputs.
- Clearer description of the model's dependency on past inflow patterns and probabilities; and that its purpose is not to predict the timing, severity and/or duration of drought conditions.
- Consideration of alternative approaches to the stochastic generation of inflows which may improve the capture of persistence of low flow conditions over matching historical distribution of annual inflows.
- A plain English summary with commentary on key modelling input changes or trends since the last yield review. Consider also adding a summary of the impact of each of the associated changes on the estimate of yield (i.e. change 'x' led to +5GLA to yield).

We also seek some clarity on:

- Do the streamflow gauges used to inform the modelling capture any releases from Sydney Water inflows/discharges from our water resource recovery facilities or advanced water treatment plants into rivers.

We would note that we have separately provided information to HARC outlining Sydney Water's climate adaptation position and approach for consideration in when incorporating climate change into their supply modelling and yield estimation.

# WATHNET Water Supply Model Review 2026

## Stakeholder Workshop – Tuesday 24 February 2026 – NSW Treasury comments

Friday, 6 March 2026

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### Overarching comments

- NSW Treasury appreciate the opportunity to contribute to the review of the WATHNET Water Supply Model 2026 and is happy to discuss our comments.
  - Melbourne Water's advice to take decision makers on the journey is supported and we'd see this as an objective of the Review. The Review's final report should clarify steps to do this, which may include the statutory required Yield Report by DCCEEW as part of their Operating Licence. Currently, WATHNET is seen as a black box that is difficult for non-specialists in the model to discern what it is telling you and how it arrived at this conclusion. Transparency and easy of understanding are necessary to support decision making.
  - WATHNET's primary purpose seems to be for strategic planning over a long (but undefined) time horizon. If the model is to be applied to support business cases to inform investment decisions, then the question of 'should we invest now' for augmentation is just as important as long term planning based on portfolios of potential investments.
  - This Review should seek to recommend an approach to include – [NSW Treasury Common Planning Assumptions](#) (CPA) – climate change scenarios within the Model to avoid out of model adjustments. If other climate scenarios or modelling exist, then an understanding is required about what they are and how they might be used in addition to the CPA.
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### Stakeholder Review Questions

Is the model providing the information required?

- WATHNET is strong at simulating storage trajectories, yield and overall system performance, but is not designed to answer the policy question (e.g. investment decision) such as 'build now versus wait' on its own. There are two separate but related needs from this model. It's our understanding that WATHNET cannot directly estimate the risk of failure at any point in time, or the cumulative risk of failure year by year.
- The Review should consider clearly mapping where WATHNET sits in the end-to-end decision process, to facilitate understanding on what decisions it can support and which it cannot.
- System yield is the average amount of water that can be supplied each year from Greater Sydney's water supply system on a sustainable long-term basis. (WaterNSW Model Review webpage).
- Clarification about what constitutes "long term" is needed for the model to provide useful information on system yield to decision makers – e.g. Greater Sydney's water supply system yield is currently 540GL/a which means the system can sustainably supply 540GL/a over the next x years. Consideration should also be given to whether the design criteria should be amended to include a time element.

- It would be useful for HARC to review the approach taken in other jurisdictions and consider whether clarification of what “long term” means in the definition of system yield would be an improvement. How water recycling initiatives are treated by the model and what assumptions are used.
- Clarify how WATHNET undertakes probabilistic and deterministic model and for what purpose. *Our understanding* is that (first) system yield is modelled probabilistically to stochastically generate replicates that meet system requirements, and (second) storage depletion curves are modelled deterministically using observed time series. Knowing how each of approaches is undertaken would be useful.
  - For both approaches how should the procedures used to develop replicates and depletion curves be explained to facilitate independent peer review. That is, what details need to be provided to non-specialist interested parties explaining what has been done and why it is deemed acceptable. This aids transparency during the decision-making process.
  - Note, if the above incorrectly characterises these concepts and process etc, Treasury is happy to discuss with HARC and other relevant experts to work through them.

Is the representation of the system appropriate?

- NSW Treasury does not have any view on system representation (e.g. dams, WTP, nodes, links etc), others are better qualified to answer this specific question. However, we seek from the Review to understand the following and how the system is affected by:
  - How water recycling initiatives are treated by the model and what assumptions are used.
  - How water restrictions are treated by the model and the specific water restriction assumptions used to calculate the yield (for example are these Levels 1-5 as outlined in the Greater Sydney Drought Response Plan 2026 and what level of water saving is assumed at each level of restrictions.
  - How water conservation is treated by the model and what assumptions are used.
  - How demand is modelled – we understand that demand is entered into WATHNET as a single long-term average, how is this modelled? What figure has been used? How sensitive is the yield estimate to the demand input? Does WATHNET use the same assumptions and data inputs as the demand model?

What is important for reporting climate change impacts?

- In determining the system yield, Water NSW must consider the impacts of climate change. System yield is the average amount of water that can be supplied each year from Greater Sydney’s water supply system on a sustainable long-term basis. Clarification about what constitutes long term would assist Water NSW to appropriately consider the impacts of climate change when determining system yield. For example, the NARcliM2 snapshots provide projections for middle of the century (2050 projection) and end of the century (2090 projection).

Are there additional references that HARC should consider?

- The review is considering if the model is fit for purpose – is the model suitable for calculating system yield, is it robust etc.? More broadly, Treasury is interested in the applications of WATHNET modelling and the use of WATHNET model outputs for economic analysis and considers that this relates to the first consultation question “Is the model providing the information required?”
- Water NSW’s Greater Sydney’s Water Supply System Yield (January 2025) Report provides the following information (see pp7-8): *Analysing yield*
  - Yield analysis can be used as a planning tool to help investigate a range of options for providing future water needs. For example, yield analysis can be used to assess the potential impacts of climate change or to investigate a range of possible management changes, including for example:

- implications of different desalination plant operating rules and staging
  - impacts of introducing environmental flows
  - short to medium term drought response measures
  - system optimisation (operating rules)
  - asset reliability impacts
  - characterisation of floods and droughts
  - determination of dam depletion rates.
- It would be useful for the independent review to consider these applications of yield analysis in detail. For example, how should yield analysis be used to assess short to medium term drought response measures? Case studies that provide more detail would be valuable. This would improve understanding of the capabilities of the WATHNET model beyond simply calculating system yield.
  - WATHNET model outputs also become inputs to a range of other models and processes, including economic modelling. It would be useful for the review to consider how the WATHNET model outputs should or should not be used to estimate the probability of different storage levels over different timeframes.
  - NSW Treasury may have additional information that could be useful to the review.
- 

## Other comments

### Specific Questions

- Over what period (in years) does the model solve for the long term? Is this time dimension relevant for timing of any augmentation in the next 5-10 years compared to Strategic Planning over 40+ years. We understand that Yield is time invariant but can depend on time also if demand changes. A clear explanation of how Yield is set over time
- What role does current storage level play in the analysis of Yield, and why? If not, how should current storage levels be used to assess water security risk?
- Can you clarify what data and assumption sit behind the modelling and what is modeller determined and what the model determines?
  - [From an economics example, like undertaking a computable general equilibrium analysis, it should be clear what inputs are used, how the modeller used them, what assumptions are made during the modelling process, and what the model does to produce output].
- Can the Model show what change (reduction or increase) in risk is achieved with different augmentations (or delay of augmentations), and if Levels of Service change what is the change in risk and cost of augmentation?
- Will the Model Review undertake similar analysis as presented by Melbourne Water with its static and dynamic analysis? If not, can WATHNET produce this type of analysis as currently developed? If not, how does the Model need to be amended, to provide this analysis?
- Given, for example, rainfall projections are highly uncertain, it is useful to understand the effect different inputs or variables have on the results and how results change with plausible differences in these variables and the procedure used to account for this uncertainty.

### Observations from the WREMA 2021 Review

- NSW Treasury seeks to understand how the following points from the previous Review have been addressed prior to this Review or will be considered in HARC's review:

- George Kuczera paper (pp61-75, in WREMA's review). Discussion on Intervention Strategy (s4.2), and the different outcomes produced by the yield and dynamic simulation analysis. As we understand, the Model produces conservative results when a yield rather dynamic strategy is taken with respect to triggering intervention - earlier and more often. We would like to understand this further and whether current analysis will undertake both approaches. What does this mean for assessing timing of augmentation?
- Section 7.0 - Information Provided for Panel, (pp34-50) is the Model able to undertake Dynamic Simulation? Does the current modelling approach follow the one outlined in this section (see p34, p41)? Is the current Yield estimate using this approach, if not why? What are the pros and cons of all feasible approaches and implications for decision making?
- Comments Dan Sheer 29th June 2021, pp110-112, point (6), is WATHNET as currently developed and the outputs it produces fit for purpose as a "driver for current investments"?
- Comments Jim Fear, pp105-109, Yield Assessment Method, is WATHNET able to undertake the analysis described, by Jim, in this section? May be useful for this Review to provide this analysis.

What needs to be fed into WATHNET for policy relevance

- For policy decisions, e.g. augmentation decisions, is it correct that WATHNET needs agreed external inputs such as:
  - acceptable probabilities of severe restrictions
  - acceptable probabilities of storage falling below critical thresholds
  - acceptable duration and frequency of restrictions
  - demand projections consistent with policy assumptions
  - climate scenarios aligned with government risk views (what data does it need? Also what climate modelling?)
  - construction lead times and decision lags
  - ....?
- With these inputs (that set constraints and goals) and the need to clearly communicate in a review, is it correct that WATHNET can simulate optimal outputs and can tell decision-makers whether simulated outcomes are acceptable from a policy perspective?

Treasury requests the following resources be shared

- Stakeholder Workshop presentation slides (including Melbourne Water's where possible).
- 2023 Climate Change Impact Assessment.
- George Kuczera's 2024 Interim Review.



## Appendix D Expert Panel Workshop Slides



# WATHNET Model Independent Review 2026

Expert Panel Workshop



Welcome placeholder

# Acknowledgement of Country

Water NSW acknowledges the Traditional Custodians of the land and water on which we work and meet here on today.

We recognise the continuing cultural and spiritual connections that Aboriginal and Torres Strait Islander People have to Country.

We pay respect to Elders past and present, and extend that respect to all Aboriginal and Torres Strait Islander peoples here today.






# Agenda

ITEM	LEAD	TIMING
1) <b>Welcome</b>	<b>WaterNSW</b>	<b>11:00 – 11:05</b>
2) <b>Acknowledgement of Country</b>	<b>WaterNSW</b>	<b>11:05 – 11:10</b>
3) <b>Introductions, project overview and aims of workshop</b>	<b>HARC – Steph</b>	<b>11:10 – 11:15</b>
4) <b>Hydrology session</b>	<b>HARC – Phillip</b>	<b>11:15 – 12:15</b>
5) <b>Lunch</b>		<b>12:15 – 1:15</b>
6) <b>Climate Change session</b>	<b>HARC – Brad</b>	<b>1:15 – 2:15</b>
7) <b>WATHNET Model session</b>	<b>HARC – Kate</b>	<b>2:15 – 3:15</b>
8) <b>Additional items and synthesis discussion</b>	<b>HARC</b>	<b>3:15 – 3:55</b>
9) <b>Next steps</b>	<b>HARC – Steph</b>	<b>3:55 – 4:00</b>
10) <b>Close</b>		<b>4pm</b>

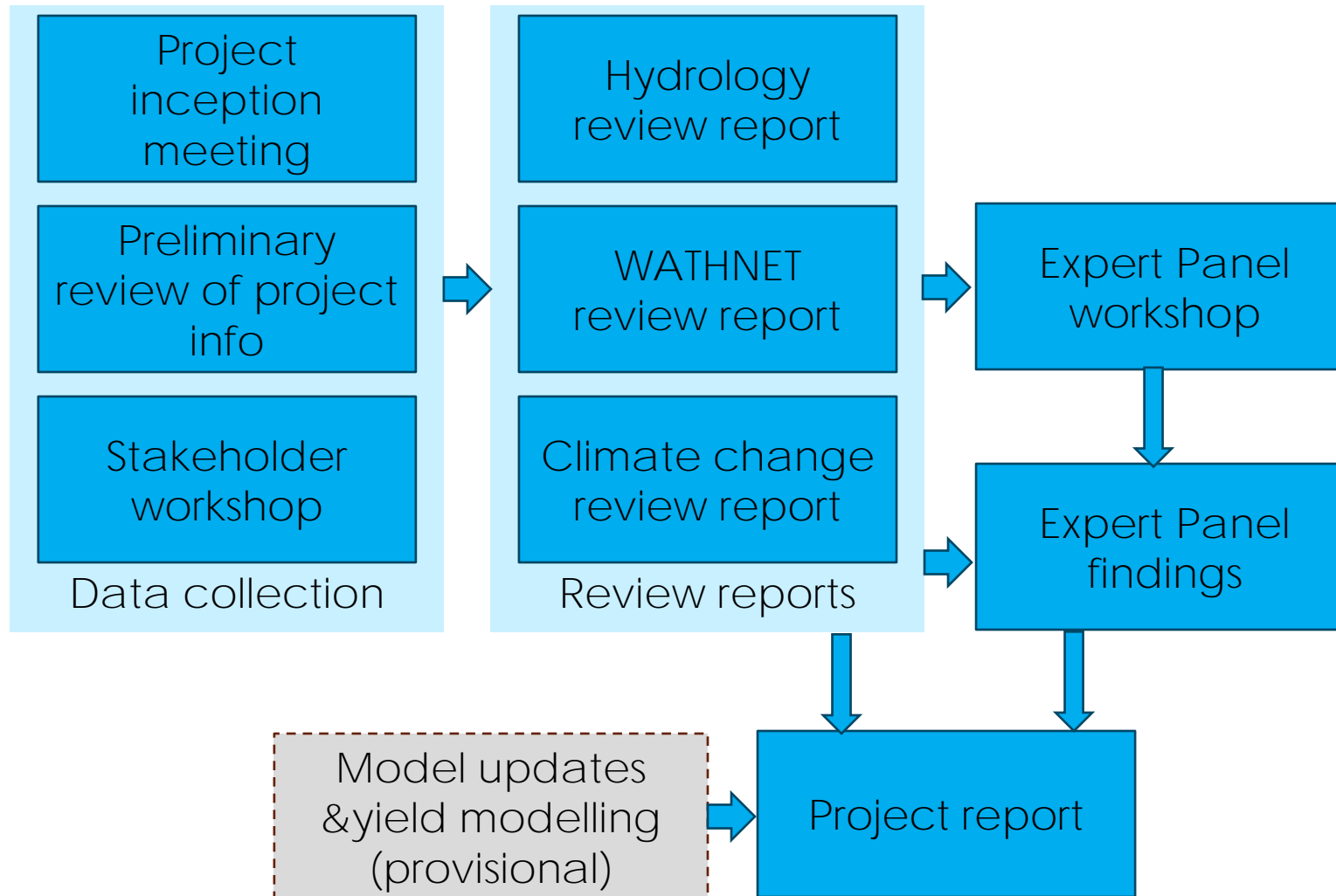
# Project team

- WaterNSW
  - Bede Johnston, Allen Lal, Angelo Breda
- HARC
  - Kate Austin, Stephanie Kermode, Phillip Jordan, Brad Neal, Michelle Ho
- Expert panel
  - Emeritus Prof George Kuczera, Dr Anthony Kiem, KS Tan, Brendan Berghout, Tim Purves

# HARC team

Kate Austin	Brad Neal	Phillip Jordan	Michelle Ho	Stephanie Kermode
Project Director, WATHNET Model Review	Climate change impact assessment	Hydrology lead reviewer	Hydrology review	Project Manager
				

# Project scope



# Aims of Expert Panel Workshop

- Opportunity for the project team to discuss key areas of the review:
  - Hydrology data sets
  - Climate Change Impact Assessment
  - WATHNET Model and yield modelling approach
  - Other suggestions to improve the modelling and its intended application

# Hydrology

# Hydrology Agenda

Review inputs

Review scope

Findings

Recommendations

- Climate data
- Streamflow data
- Stochastic data

## Hydrology review *inputs*

- WATHNET Model Review:  
Hydrology Updates by WaterNSW (2026)
- WaterNSW Rainfall-Runoff Model Development:  
Memo for WATHNET Model Review by WaterNSW (2026)
- Sample input datafiles to the WATHNET model for  
historical and stochastic climate and inflows

# Hydrology review scope

- As outlined in the WaterNSW Statement of Work:
  - “Review of the historical inflow, evaporation and rainfall datasets,
  - including proposed changes to methodology to develop historical input data for stochastic generation, and
  - advise on the suitability of the datasets for yield estimation.

# Hydrology review *findings*

- Historical data:
  - opportunities to improve the derived historical inflows
- Stochastic data:
  - the stochastic generation method is fit for the purpose
  - opportunities to:
    - improve data inputs used to calibrate the model
    - improve approach to generating the data
    - improve application of stochastic data
    - incorporate paleoclimate information

## Hydrology review *recommendations*

1. Undertake an update of historical inflow calculations using unbiased, quality-controlled data inputs and a consistent set of methods
2. Quality check all climate data inputs for non-climatic trends or step changes and use consistent climate data inputs for both estimating inflows and WATHNET inputs (i.e. lake rainfall and evaporation)
3. Re-calibrate rainfall-runoff models to be suitable for estimating yield. This will enable the infilling and potential extension back in time of historical inflows and assessment of climate change impacts on yield
4. Develop and maintain documentation of data sources and methods.

# Individual high priority recommendations

Climate data

Streamflow data

Stochastic data

# Individual high priority recommendations: climate data

- #26: Develop and maintain documentation on the differences between the rainfall and reservoir evaporation inputs used directly in the WATHNET model and those used in the CMCR inflow calculations. Focus on differences in underlying data sources and any adjustments applied to the data prior to use.
- #12: Adopt estimates of lake evaporation using Morton-based methods for deep lake evaporation for reservoirs deeper than 30 m
- #8: Use gauged rainfall for deriving streamflow in all applications, unless gridded rainfall is the only available source of data

# Individual high priority recommendations: streamflow data (1 of 2)

- #18: Replace unknown water balance values prior to the 1960s with CMCR estimates. If CMCR estimates cannot be applied for these locations and time periods, replace with results from rainfall-runoff models that are suitable for yield estimation
- #27: Develop and maintain documentation on the differences between inflows calculated using legacy CMCR approaches and those calculated using the current CMCR approach. For each dam, cumulative inflow plots for the period 1960–2025 showing both legacy and current CMCR-derived inflows should be produced, to identify discontinuities or divergence in cumulative behaviour due to change in methods
- #25: Seek to improve rainfall-runoff model calibration accuracy by exploring the use of at-site rainfall inputs, alternative model calibration strategies, or alternative model structures, with the aim to use the time series outputs from these models directly in water resources modelling

# Individual high priority recommendations: streamflow data (2 of 2)

- #22: Re-calibrate Sacramento to ensure suitability for yield estimation including incorporation of more recently collected streamflow data
- #23: Replace existing HSPF approach used to estimate reservoir inflows for Tallowa, Fitzroy Falls, Wingecarribee and Woronora dam inflows with modelled flows from Sacramento (calibrated for yield estimates)
- #23: Replace regression-based flows for Nepean, Avon and Cordeaux if calibrated Sacramento models produced improved statistics compared with regression equations
- #24: Develop an understanding of existing rainfall-runoff models from NSW DCCEEW

# Individual high priority recommendations: stochastic data

- #30: Ensure calibration of stochastic simulation parameters is based on a reasonably homogenous period of rainfall-runoff behaviour
- #33: Examine the impact of using  $k = 5$  and  $k = 10$  nearest neighbours on the metrics of system performance
- #28: Determine the number of replicates needed under historical climate conditions to achieve a stable estimate of yield
- #32: Generate synthetic data using  $k = 5$  and  $k = 10$  and investigate the prevalence of monthly temporal patterns for near-average or “wet” years being applied to synthetic low flow years

# Climate Change

# Workshop Agenda – Climate Change

- Overarching findings and recommendations
- Historical climate change, hydroclimate data stationarity
- Climate change scaling factors including climate reference period for the scaling and parameters being scaled
- Climate projection data source, climate model selection, emission pathway selection
- Low likelihood, high impact climate change scenarios
- Managing expectations of climate change certainty over time

# What was provided for review?

- WaterNSW's 2023 *Climate Change Impact Assessment for Greater Sydney Water Supply System Using NARClIM1.5 data* that was prepared to support Sydney Water's *Long-Term Capital and Operational Plan*.
- Summary of assumptions and methods that WaterNSW is adopting in its 2026 climate change impact assessment
  - method refinement and application in progress

# Scope

- Under Clause 35(2) of its operating licence, WaterNSW must conduct its activities “in a manner that considers the impacts of climate change” when it is determining or re-determining the system yield
  - New clause that was not in place for previous reviews for IPART
- Further regulatory and stakeholder policy context provided in the HARC review

# Over-arching findings from HARC review

1. **“The climate change impact assessment undertaken in 2023** for the Long-Term Capital and Operational Plan **was fit-for-purpose**, reflecting contemporary good practice at the time of that assessment. The assessment included WaterNSW documentation on methods, assumptions, their justification, and quality control/assurance checks.”
2. **“It is difficult for HARC to fully assess the suitability of WaterNSW’s 2026 climate change impact assessment methods and assumptions**, because those methods are currently being developed and applied, and have not yet been documented. The review recommendations provided by HARC on the 2026 methods offer an opportunity for WaterNSW to consider and adapt its methods as they are implemented.”

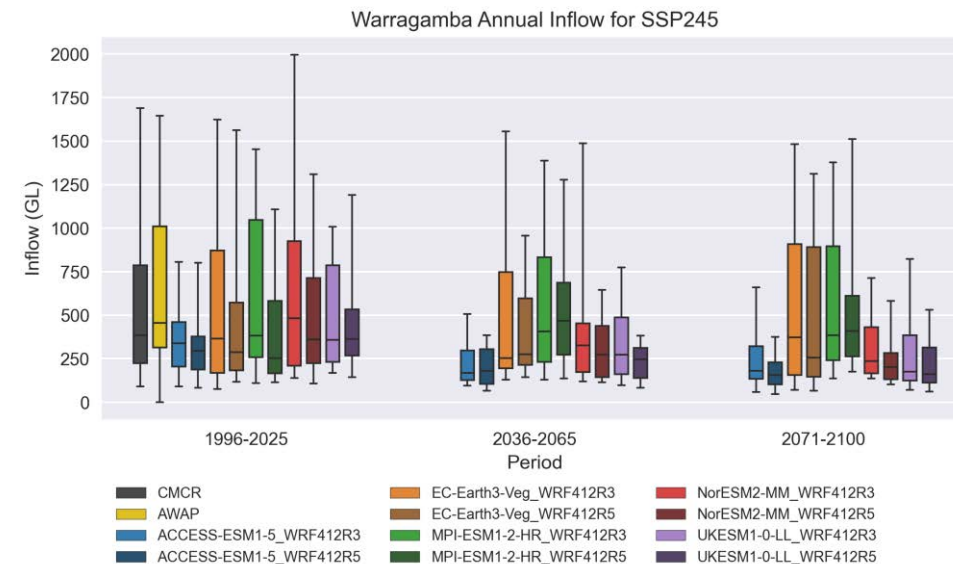
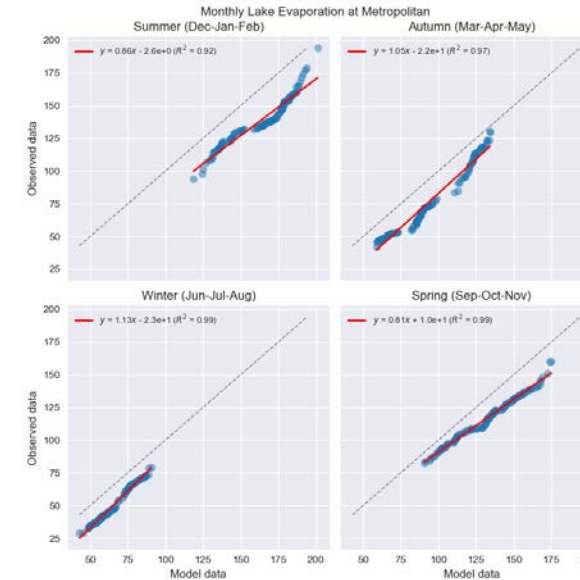
# Comparing with procedure from 2022/2023 assessment

## Doing similarly:

- Workflow
- Input data analyses
- Source models (SAC-SMA)
- Result data analyses
- Bias correction / CC factors

## Doing differently:

- Using NARCLiM2 data (10 models)
- WATHNET model with lake data
- SSP2 and SSP3 instead of RCP4.5 and RCP8.5
- Future horizon time slices
  - 30-year time slices
  - Near future = 2040 to 2069
  - Far future = 2070 to 2099



# Over-arching recommendations from HARC review

1. **“To continue to test recent innovations in climate change impact assessment methods** with the aim of transitioning to improved methods where they are demonstrated to provide benefits locally.”
  - i. Co-variate analysis
  - ii. Pattern scaling
2. **“To continue to collaborate with other agencies to achieve consistency in climate change assumptions across NSW Government stakeholders where it is reasonable to do so.”**
  - i. Ongoing participation in DCCEEW’s metropolitan climate change working group
  - ii. Continued alignment with NSW Government Common Planning Assumptions
  - iii. More transparent sharing of information about assumptions and methods with stakeholders

# Over-arching recommendations from HARC review

3. **“To continue to analyse and report on the full range of yield estimates from all NARClIM2.0 projections, rather than focussing on only a single climate future”**
4. **“To revisit rainfall-runoff model calibrations, given the importance of these models for estimating climate change factors for inflows to the water supply system.”**

# Individual recommendations from HARC review

- 22 specific recommendations, 3 of which were to recommend retaining a current practice
- **Selected 2 low effort recommendations** that would be beneficial to implement quickly:
  - **#11: Climate model selection:** For reporting purposes, report on at least the highest impact climate scenario under SSP2-4.5, and the range of impacts from all NARClIM2.0 runs.
  - **#16: Climate change scaling factors:** When using the time slice method to calculate change factors, align the climate reference period with guidance from DCCEEW and the Metropolitan Climate Change Working Group (currently 1976-2005).
    - If not changed quickly, this would be high effort to change later

# Individual recommendations from HARC review

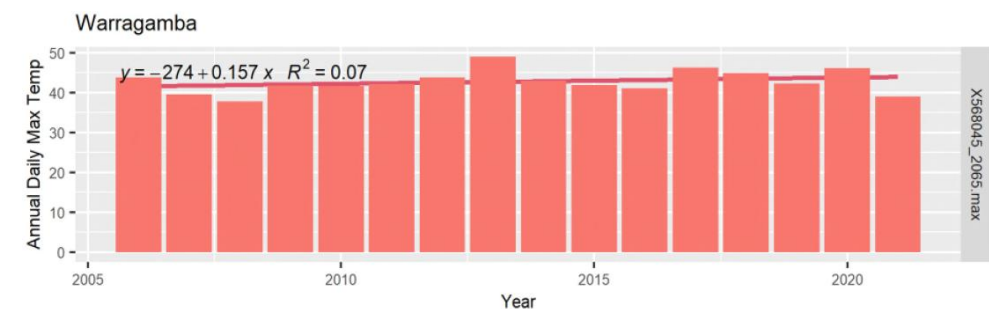
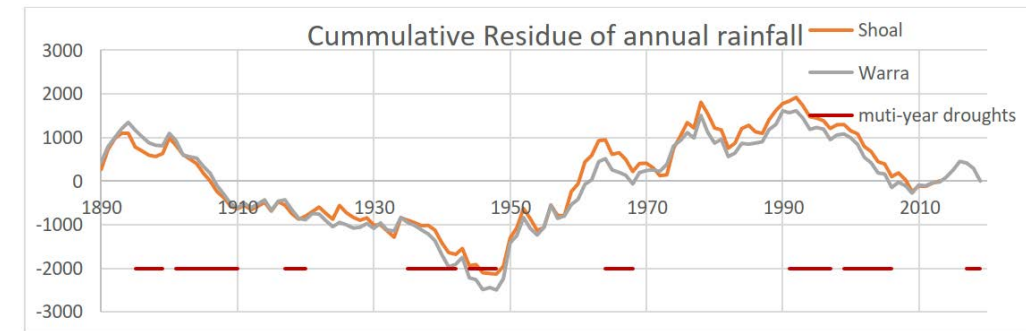
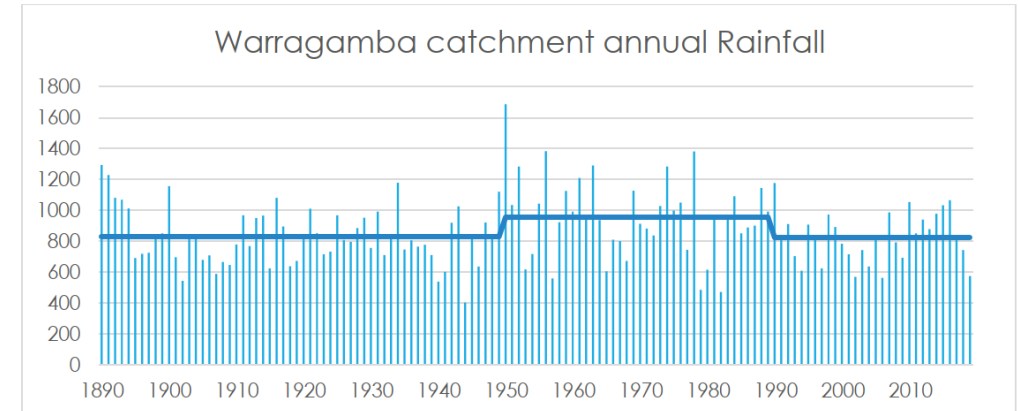
- **Selected 4 moderate to high effort recommendations that could be material to yield assessment outcomes:**
  - **#4: Rainfall-runoff model calibration accuracy:** Seek to improve rainfall-runoff model calibration accuracy by exploring the use of at-site rainfall inputs, alternative model calibration strategies, and/or alternative model structures, with the aim to use the time series outputs from these models directly in water resources modelling if suitable calibration accuracy can be achieved.
  - **#5: Rainfall-runoff model calibration accuracy:** Re-run climate change yield assessment if improved rainfall-runoff model calibration can be achieved.
  - These two recommendations already discussed as part of the hydrology review session of this workshop

# Individual recommendations from HARC review

- **Selected 4 moderate to high effort recommendations that could be material to yield assessment outcomes:**
  - **#1: Historical climate change and hydroclimate data stationarity:** When considering the influence of climate change on hydroclimate observations, utilise formal statistical testing to identify any non-stationarity, and co-variate analysis using air temperature as a co-variate to de-trend rainfall and PET data for historical global warming. Air temperature data can be directly de-trended.
  - **#17: Climate change scaling factors:** Support local testing of the pattern scaling approach by the Metropolitan Climate Change Working Group and, together with other stakeholders, transition to its use for climate change projections, if it is found to be more fit-for-purpose locally than the time slice method in reducing the signal-to-noise ratio from the climate change projections.

# Historical climate change and historical data stationarity

- If the hydroclimate baseline is non-stationary due to global warming, then yield at the current level of global warming could be over- or underestimated
- WaterNSW's 2023 analysis has some good visual checks for non-stationarity (see charts to the right) and a good understanding of instrumental data availability
- Could be strengthened by:
  - formal statistical testing
  - co-variate analysis using temperature as a co-variate to de-trend PET, rainfall, and runoff
  - direct de-trending of air temperature



# Climate change scaling factors

- 2023 & 2026 WaterNSW approach uses reference and future time slices from climate model outputs to calculate change factors – which approach is best?

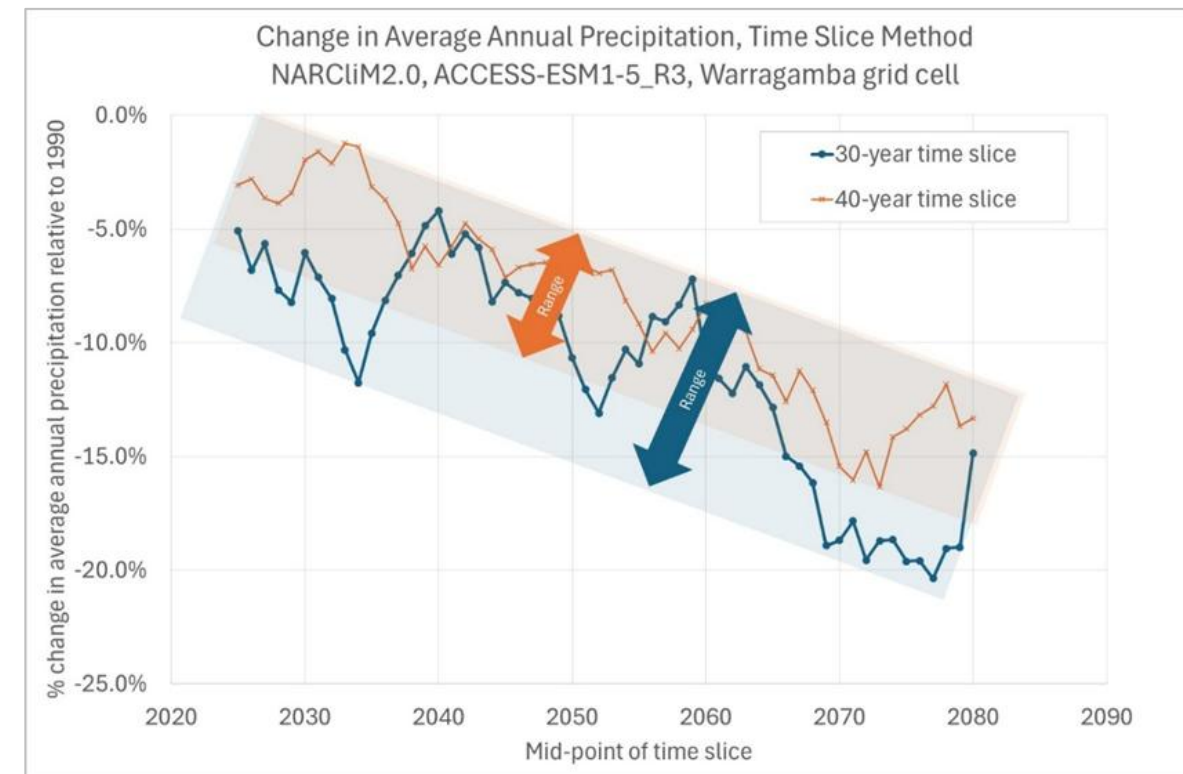
Historical time slice period (and duration in years)	Future time slice duration (years)	Reference
1980-2009 (40 years)	40	WaterNSW yield assessment (WaterNSW, 2023)
1996-2025 (30 years)	30	WaterNSW's 2026 approach
1976-2005 (30 years)	30	DCCEEWS Regional Water Strategies, DCCEEWS draft framework for selecting and preparing climate change data, DCCEEWS draft metropolitan climate change technical guidance (DCCEEWS (NSW), 2026a), (DPE, 2022), (DCCEEWS (NSW), 2026b)
1990-2009 (20 years)	20	AdaptNSW Interactive Climate Change Projections Map (NSW Government, 2025)

# Climate change scaling factors

- 2023 & 2026 WaterNSW approach uses reference and future time slices from climate model outputs to calculate change factors – which approach is best?

## HARC's view:

- Water availability under climate change can be sensitive to these assumptions (see chart)
  - But needs further testing to confirm
- There is value in alignment of climate change projection assessment methods across similar applications in the Greater Sydney region

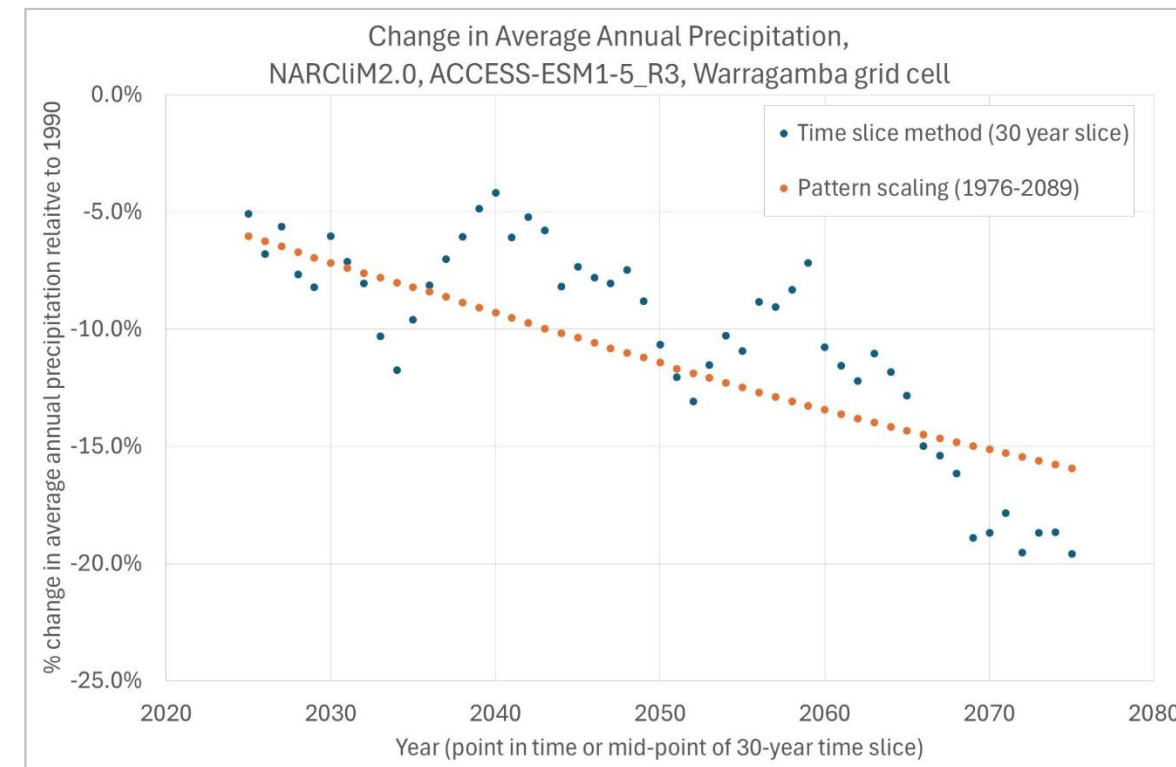


# Climate change scaling factors

- 2023 & 2026 WaterNSW approach uses reference and future time slices from climate model outputs to calculate change factors – which approach is best?

## HARC's view:

- Pattern scaling would remove the noise in the climate model outputs to reveal the climate change signal, avoiding double counting of climate variance when applying change factors to the hydroclimate baseline
  - But needs further testing to confirm

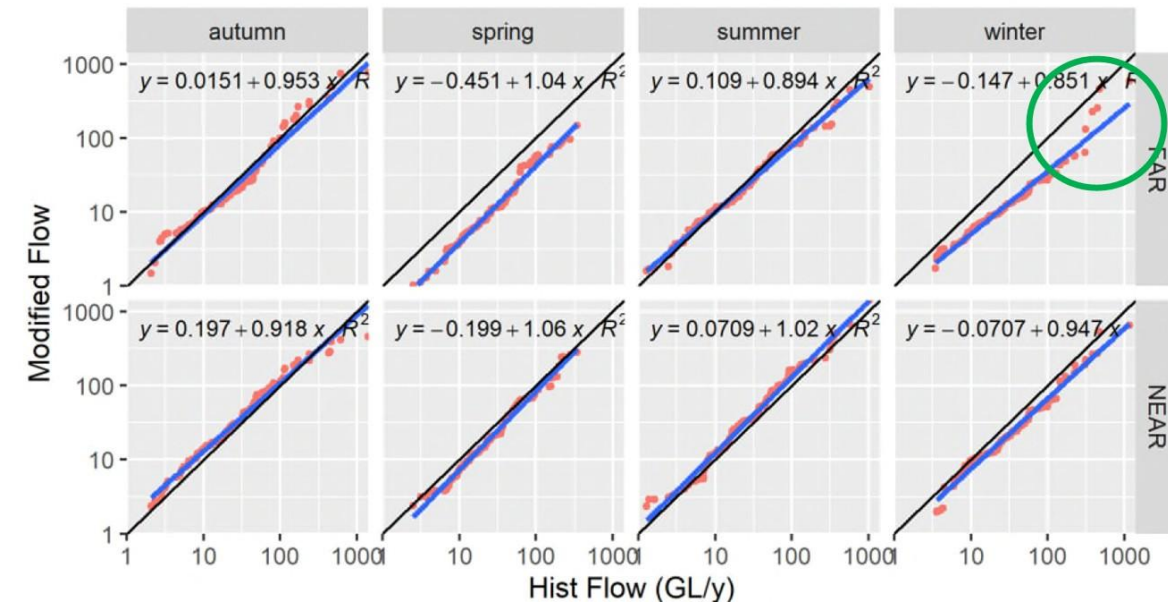


# Climate change scaling factors

- 2023 & 2026 WaterNSW approach uses reference and future time slices from climate model outputs to calculate change factors – which approach is best?

HARC's view:

- Simplify the scaling approach and only differentiate the scaling factors at very high rainfall and runoff to align with ARR guidance
  - But needs further testing to confirm



## Climate projection data source, climate model selection, emission pathway selection

- NARClIM2.0 is a NSW Government Common Planning Assumption and is being used by WaterNSW
- NARClIM2.0 has:
  - 3 emissions pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0), representing future emissions uncertainty
  - 10 projections per emissions pathway representing climate model uncertainty
- WaterNSW's 2023 approach analysed all available projections
- HARC's view that the 2026 approach should:
  - Calculate change factors for all available projections
  - Select storylines that represent a range of climate futures, rather than an ensemble mean or median
  - One of those storylines needs to align with Sydney Water requirements (lowest yield under SSP2-4.5)

## Low likelihood, high impact climate change scenarios

- NARClIM2.0 is our best modelled representation of future climate
- Whilst low likelihood, there are many reasons why the future climate change could be different than projected by NARClIM2.0
- What if this were to occur?
- HARC's recommendation: WaterNSW consider the possibility of one or more possible low likelihood, high impact climate change scenarios derived independently from the direct use of climate model outputs
  - Not an easy task that anyone has done well to date
  - One approach is to tackle it from a system resilience perspective, with hypothetical climate change causal pathways linked to a shock event

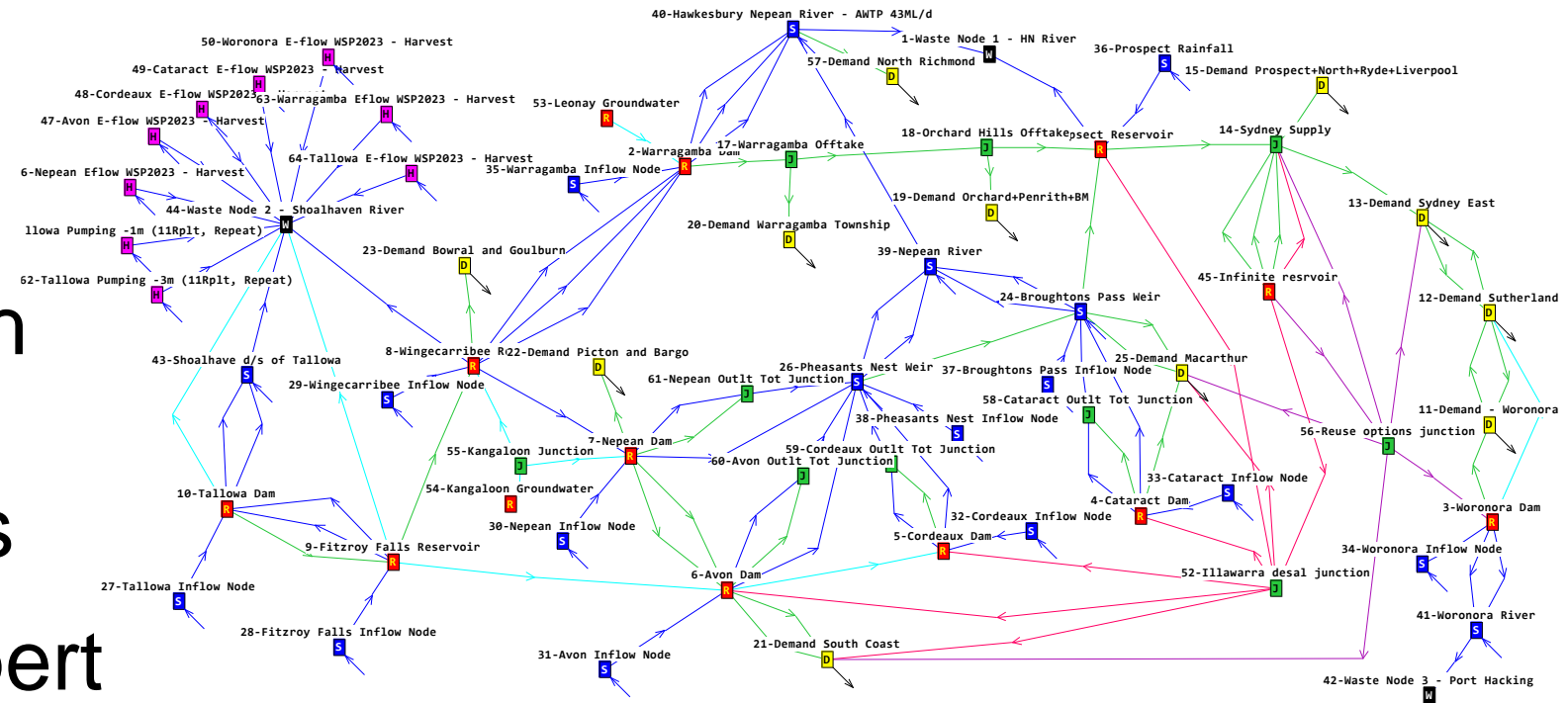
## Managing expectations of climate change certainty over time

- Climate model projections, historical observations, and assessment methods will change over time
- Need to educate stakeholders about this to manage any unrealistic expectations of certainty they may have
- HARC's recommendation: WaterNSW document the main reasons for changes in yield estimates under projected climate change in the 2026 assessment, relative to the 2023 assessment.

# WATHNET Model

# Workshop Agenda – WATHNET model

- Review process
- General findings
- Discussion of high priority recommendations
- Discussion of expert panel thoughts on review report



# Review inputs

- Documents:
  - Past review reports and available model documentation
  - Regulatory documents (e.g. Water Sharing Plan, WaterNSW Operating licence)
- Technical data:
  - WATHNET model and input files
- Stakeholder inputs:
  - Discussions at the Stakeholder Workshop and subsequent information provided by stakeholders
  - Meetings with stakeholders and WaterNSW staff
- Findings from the hydrology and climate change reviews

# Review scope and aims

- Scope
  - To review the WATHNET model and yield modelling approach including implementation of most recent review recommendations
- Aims
  - To confirm the modelling approach reflects industry best practice
  - To identify opportunities for improvement
  - To take into account feedback from stakeholders

# Review process

- Review of the implementation of 2021 and 2025 review recommendations
- Review of model setup:
  - Are the physical characteristics and hydraulic constraints of the system correctly represented and up to date?
  - Is the level of detail/discretisation fit for purpose?
  - Are rules and constraints correctly represented?
  - Do operating rules and constraints reflect current practice?
  - Calibration / validation: does the model replicate recent system behaviour?

# Review process

- Review of yield modelling
  - Review of current approach
  - Benchmark against water security analysis across Australia (modelling approach, design criteria, etc)
  - Discuss the pros and cons of different approaches
- Review recommendations made and prioritised

# General findings

- 70 review recommendations made (11 high, 40 medium & 19 low priority)
- Recommendations from previous reviews (2025, 2021)
  - most have been implemented. Outstanding recommendations have been retained, removed or updated as part of this review
- Model setup
  - there are a range of opportunities to enhance model defensibility by applying constraints, verifying assumptions, undertaking model validation, documentation, etc
- Yield modelling approach
  - Approach constrained by current licence conditions
  - Opportunities for enhancement and/alternate approach in future

# High priority recommendations

- Model settings related to inflows:
  - **Recommendation:** Ensure alignment of model settings with those used for inflow derivation, i.e. rating tables, climate inputs to storage, inflow factoring (e.g. lake boundary adjustment)
- Model settings related to demand split / eflows:
  - **Recommendation:** Make required updates to demand distribution and eflows prior to 2026 yield modelling

# High priority recommendations

- Representation of Seasonal Fraction:

*Demand = seasonal fraction \* demand zone disaggregation fraction \* restFrac \* annual demand*

where Seasonal Fraction is a monthly climate driven pattern derived by Sydney Water

Seasonal Fraction is an input to the stochastic data generation process

- **Recommendation:** Ensure that the relationship between historic climate and historic seasonal fraction is maintained under stochastic data generation. Consider representing the seasonal fraction calculation as a function in the model. This will also help for climate change runs

# High priority recommendations

- Maximum capacities:
  - **Recommendation:** Apply pipe/pump/canal/tunnel maximum capacities where they are not currently set in the model
- Long Term Average Annual Extraction Limits:
  - WaterNSW advise that LTAAEL would be changed if hit
  - **Recommendation:** Since LTAAEL are specified in the WSP it is recommended that these be applied so that it can be understood whether they are a constraint or not

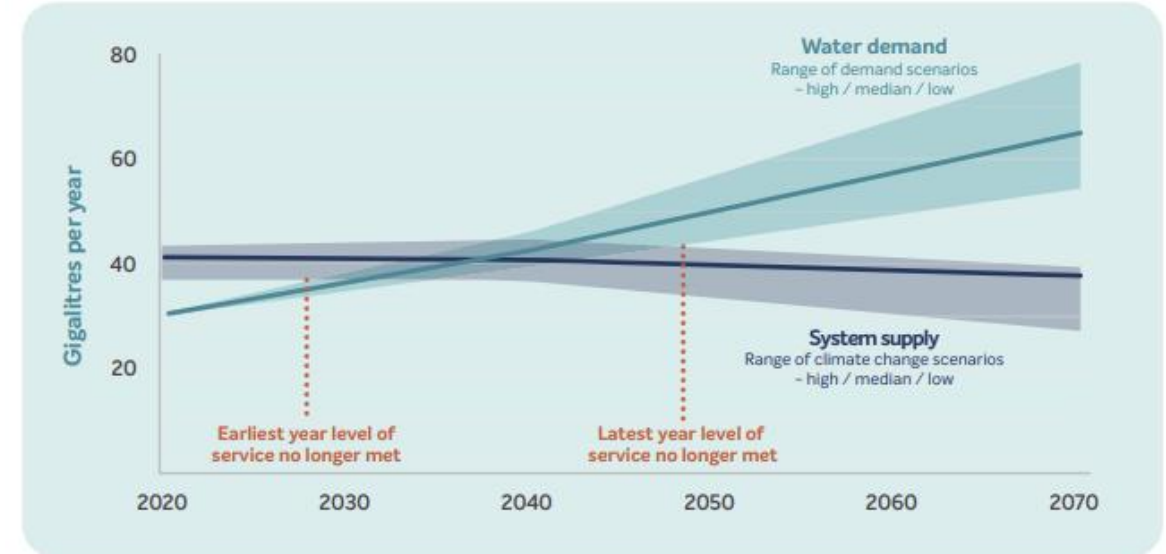
# High priority recommendations

- Model calibration and validation
  - **Recommendation:** Calibrate and validate the model to verify assumptions (losses, mass balance, operating rules) explain any differences and enhance model defensibility
- Documentation
  - **Recommendation:** Complete and maintain consolidated documentation of the model, derivation of model inputs and approach to yield modelling. Consider approaches that allow for live updates and tracking of model runs and version control

# High priority recommendations

- Yield modelling approach:
  - Steady state modelling is currently used. This approach is useful for showing the difference between supply (yield) and demand
  - Dynamic modelling is advantageous in systems with long storage memory, but the ability to use this approach constrained by the current licence condition requiring yield to be calculated

Example of a supply-demand balance under a range of climate and demand scenarios



# High priority recommendations

- Yield modelling approach:
  - **Recommendation:** Retain the current steady state yield modelling approach
  - **Recommendation:** Consider a dynamic modelling approach if operating licence conditions and design criteria change

	Steady state modelling of yield	Transient state modelling of system behaviour under projected demands	Transient state modelling of yield
Can be run with existing stochastic data set (no of replicates)	✓	✗	✗
Better represents state of a system with large storages	✗	✓	✓
Provides information on the gap between supply and demand over time	✓	✗	✓
Straightforward to communicate method and results	✓	✗	✗
Complies with current WaterNSW operating licence requirement	✓	✗	✓
Provides outputs useful for a range of other purposes	✗	✓	✗

## Expert panel initial thoughts on WATHNET review report

- Do we need to discuss any other lower priority recs?
- Other feedback?

# Additional items

## Alternative, additional or complementary system performance measures or design criteria

- Current design criteria:
  - Security: storages do not approach emptiness (defined as 5% of water in the operating storage) more often than 0.001% of the time, or one chance in 100,000 in any one month.
  - Robustness: imposed water restrictions should not occur more often than once in every ten years on average.
  - Reliability: imposed water restrictions should not last longer than 5% of the time on average, or 5 months in 100 months.

# Current design criteria

- Security: <5% storage 1 in 100,000 months
  - Basis of the 5%? Ideally related to a required reserve volume that is linked to a practical measure (e.g. to enable X months of in-house use until an augmentation can be implemented)
  - Issues with very low likelihood criteria (basis, uncertainty)
- Robustness: Restrictions  $\leq 1$  in 10 years
  - In line with industry norms. Usually set taking into account stakeholder cost/risk appetite
- Reliability: Restrictions  $\leq 5\%$  of months
  - In line with industry norms. Usually set taking into account stakeholder cost/risk appetite

# Other design criteria & performance measures

- Other design criteria:
  - Minimum level of service (critical human water needs), which can lead to identification of an enduring supply to match that need
  - Maximum likelihood of severe restrictions, which can be easier for stakeholders to interpret than the existing reliability criterion.
  - Naming conventions – robustness and reliability have common meanings that are different from the terms as used by WaterNSW. The robustness measure is actually an indicator of reliability, and the reliability measure is actually an indicator of restriction duration.
- Other performance measures:
  - Likelihood of restrictions or shortfalls in each year over the planning horizon – easier to work with than yield when desired level of service is being explored, and better suited for non-stationary inputs
  - Cost – including cost to urban water service providers and cost to customers
  - Range of other indicators used in option assessment (e.g. river health, social acceptance, etc.)

# Any other Expert Panel recommendations for improvement or consideration



- Discussion

# Next Steps

<u>Task</u>	<u>Due</u>
<ul style="list-style-type: none"> <li>▪ Expert Panel members review findings               <ul style="list-style-type: none"> <li>▫ HARC to incorporate Expert Panel workshop discussion &amp; review findings into Project Report</li> </ul> </li> </ul>	28 April
<ul style="list-style-type: none"> <li>▪ <i>Provisional: selected model updates &amp; yield calcs</i></li> </ul>	
<ul style="list-style-type: none"> <li>▪ Draft Project Report</li> </ul>	1 June
<ul style="list-style-type: none"> <li>▪ Final Project Report</li> </ul>	19 June
<ul style="list-style-type: none"> <li>▪ WaterNSW submit to IPART</li> </ul>	30 June

# Workshop close



## Appendix E Expert Panel Workshop Minutes

## Minutes

<b>Meeting</b>	Expert Panel Workshop		
<b>Project</b>	WATHNET Model Independent Review 2026	<b>Project No.</b>	NSW00097
<b>Manager</b>	Stephanie Kermode	<b>Phone No.</b>	0411 966 554
<b>Location</b>	RM-6PSQ-Menindee Lakes – West; Teams	<b>Date/Time</b>	21 April 2026; 11:00-4:00
<b>Present</b>	WaterNSW: Allen Lal, Bede Johnston, Angelo Breda, Michelle Zhang, Lorena Oliveira, Jason Martin HARC: Kate Austin; Stephanie Kermode, Phillip Jordan, Brad Neal*, Expert Panel: Brendan Berghout, KS Tan*, Tim Purves, George Kuczera, Anthony Kiem NSW DCCEEW: Mohammad Mortazavi-Naeini, Hunter Water: Natalie Lockart Sydney Water: Jonathon Dixon *via videoconference		
<b>Apologies</b>	Simon Williams (DCCEEW), Michelle Ho (HARC)		
<b>Distribution</b>	Attendees		

Item
<p><b>Agenda Item 1 – Opening discussion</b></p> <p>The workshop opened with discussion led by Allen and Bede, setting context around the Operating Licence (OL) update and the need to incorporate climate change explicitly into yield, including how this is reported and communicated.</p> <p>There was early agreement that the challenge was not whether to include climate change, but how to do it in a way that is defensible, implementable and decision-relevant. Participants noted the accumulation of historical approaches, transitions in methods and inconsistent documentation.</p> <p>Steph emphasised that this review was an opportunity to reset practice, noting that without clarity and traceability, confidence in downstream results was at risk. Several participants commented that the hydrology update was confronting, particularly in revealing how many different methods have been used over time.</p> <p>GK stated that returning to raw or traceable data was the single most important step, with others agreeing that everything depends on this.</p> <p>Online participants (including MZ, BN, NL, KS) reinforced the need for a clear path forward and consistency.</p>
<p><b>Agenda Item 4 – Hydrology</b></p> <p><b>1. Data inputs and provenance</b></p> <p>Discussion moved to hydrology inputs, including the <b>CMCR spreadsheet</b>, net rainfall on storages, palaeoclimate and climate datasets.</p> <p>There was strong concern expressed by multiple participants (<b>CK, GK, JM, BB</b>) about <b>data provenance</b>, particularly for rainfall, evaporation and early streamflow inputs.</p> <p><b>George highlighted this as foundational</b>, with repeated statements that issues here materially affect yield and must be prioritised over more sophisticated modelling refinements.</p> <p>Participants discussed:</p> <ul style="list-style-type: none"> <li>• Legacy datasets and transitions in approach,</li> <li>• Limited documentation of why methods changed,</li> <li>• Difficulty understanding provenance of gridded datasets (AWAP, SILO).</li> </ul> <p><b>JM</b> noted extensive work in earlier studies looking at gauge history, particularly in high rainfall regions.  <b>BB</b> gave examples where gridded rainfall substantially underestimated true rainfall due to orographic effects</p>

(e.g. SILO 200 mm/a vs nearby gauge 1400 mm/a).

**GK** and **KS** stressed that **consistency** is critical, even if imperfect methods are retained temporarily.

## 2. Rainfall–runoff (R–R) models

Rainfall–runoff modelling drew extensive discussion.

**GK** stated that any R–R model used must be **fit-for-purpose**, noting required characteristics:

- Acceptable monthly-scale performance,
- Mass balance maintained,
- Minimal bias.

There was acknowledgment that:

- Some legacy models (e.g. HSPF) can no longer be run,
- Simpler models (e.g. GR4J) may perform better in practice,
- Poorly performing models should not be retained simply for consistency.

**George reinforced that model performance matters more than model type**, and that poor NSE scores or bias should be a trigger for reconsideration, not rationalisation.

Calibration strategy was debated:

- **Split-sample testing** was strongly supported (**GK, JM**),
- Calibration timestep should align with the **stochastic model timestep** (i.e. focussing primarily on years or seasons, with a secondary focus on monthly statistics. Performance at shorter timesteps is of considerably less importance, given that WATHNET runs on a monthly timestep),
- There was reluctance to assume stationarity in rainfall runoff characteristics due to vegetation change, though some participants felt bushfire impacts on stationarity in runoff characteristics in Sydney water supply catchments, which are generally Mixed Species Eucalypt Forests, than in Melbourne's water supply catchments, which have a larger proportion of Ash type forests.

## 3. Evaporation, streamflow and stochastic data

Lake evaporation (including stratification effects) was discussed, noting that both sides of the water balance must be treated consistently (**Michelle's recommendation referenced**).

Streamflow data raised concerns about early inputs:

- **JM** referenced mass balance approaches at the coffer dam pre-1960,
- Contributors noted uncertainty around dam commissioning periods,
- Negative inflows in CMCR were due to uncertainties in recorded inputs (storage levels and / or releases) and should be checked.

Stochastic data generation was discussed:

- **K values**, for the kernal-nearest neighbour algorithm and memory length may influence dry-year behaviour,
- **Specification here directly impacts yield and system performance**,
- Several participants stressed the need to preserve correlations and not repeatedly sample the same low-flow patterns, which is often a consequence of selecting a low k value, such as k=1.

## Agenda Item 6 – Climate change representation

Participants broadly agreed that:

- Climate change must be represented as a **range of outcomes**, not a single future,
- Stakeholders need exposure and consequence, not just means or medians.

**Several participants noted that climate change is already affecting yield**, and continuing to frame it as a future problem undermines credibility.

## 4. Methods and reference periods

There was extensive debate on:

- Time slicing vs pattern scaling,
- Reference period selection,
- Detrending historical data.

**BN** and **GK** highlighted that time slicing is sensitive to sampling error, while **pattern scaling and covariate approaches** provide robustness.

**AK** noted deliberate oversimplification of some approaches to ensure implementability given NarClim limitations.

Participants questioned why different agencies use different reference periods (e.g. DCCEW vs MDBA vs WaterNSW). It was generally agreed that past policy choices were understandable at the time but may no longer be defensible.

## 5. Covariates and non-stationarity

Covariate approaches (temperature–streamflow relationships) attracted strong support:

- Viewed as data-driven and transparent,
- Better aligned historical and projected datasets,
- Useful alongside, not instead of, climate models.

**Alignment between historical and climate-adjusted projections as critical for defensibility**, particularly for Treasury and Ministerial settings.

Palaeoclimate data was discussed, with **AK** and **BB** advocating longer reconstructions (1000–2000 years), noting that even 800-year records may miss known extreme droughts.

## Agenda Item 7 – WATHNET model and yield calculation

### Role of yield vs dynamic modelling

There was consensus that yield alone cannot answer when augmentation should occur.

George (GK) strongly supported greater use of dynamic modelling, stating that yield analysis cannot identify decision points and lead-time needs. Noted that recommendations should not be constrained by current licence conditions. A more positive recommendation in relation to dynamic modelling was preferred.

Steph noted that dynamic modelling could be particularly compelling if it demonstrated:

High likelihood of restrictions within short, politically relevant timeframes (e.g. an election cycle),  
Reduced lead time for augmentation decisions.

Yield was still seen as useful, but no longer sufficient as the primary strategic planning tool.

Calibration, validation and documentation

Participants supported:

Forced-operation testing and validation,

Better alignment between assumptions used for inflow calculation and those embedded in WATHNET,  
Version control as standard practice.

Operational constraints, water quality and Levels of Service were raised repeatedly as being inadequately represented.

■

## Agenda Item 8 – Discussion

Levels of Service and communication

There was discomfort with very low-probability criteria at extremely low storage levels.

GK, KS and BB discussed examples where minimum operating levels were better defined by hydraulics, water quality and access, rather than abstract probabilities.

LOS must be explainable in plain English, focused on consequences rather than statistics, especially for Ministers and Treasury.

Paleoclimate datasets, governance and planning culture were discussed.

Participants expressed concern about:

- Stop–start planning damaging industry confidence,
- Capital inefficiencies from delayed decisions,

- The need for modelling to support **holistic conversations** across demand, supply, water quality and climate risk.

There was agreement that the current review provides a genuine opportunity to **change practice**, not just refine methods.



## Appendix F Expert Panel Written Responses

# Report on HARC WATHNET Model Independent Review

29 April 2026

George Kuczera

# 1 Preamble

The three HARC reports present about 130 recommendations. In writing this report, the reviewer has focussed on the more consequential recommendations, particularly those that are contestable, and on issues considered important but in need of more analysis or clarification. No specific list of recommendations is made as it should be clear from the narrative what is the reviewer's position.

The review is organized in three sections with each section dealing with a specific HARC report.

## 2 WATHNET Model and Yield Modelling Approach

### 2.1 Yield Modelling Approach: A Fit-for-Purpose Lens

The review of the yield modelling approach and ensuing recommendations are considered the most consequential part of the HARC's report as HARC's recommendations have the most significant policy implications. HARC made two key recommendations:

- Recommendation 69 "Retain the current steady state yield modelling approach"
- Recommendation 70 "Consider a dynamic modelling approach if operating licence conditions and design criteria change"

These recommendations are not well supported by the analysis in the report and, if taken out of context, give the impression that the status quo can be maintained.

It is recommended that HARC carefully reconsider their narrative and ensure recommendations better convey contemporary understanding of the yield approach and the opportunities offered by alternative methods.

The intent of the remainder of this section is to explain the basis for this recommendation.

#### 2.1.1 A Fit-for-Purpose Lens

Implicit in the operating licence is the presumption that the yield approach and its performance metrics are fit-for-purpose. One would expect a fit-for-purpose methodology would inform how the security of the system evolves into the future under growing demand and changing climate. If security is found wanting, the methodology would inform what actions are needed to restore cost effectively an acceptable level of security. Any review of the yield approach should use this fit-for-purpose lens.

The response from Treasury highlights the need for such a perspective. A key comment from that response was:

"WATHNET's primary purpose seems to be for strategic planning over a long (but undefined) time horizon. If the model is to be applied to support business cases to inform investment decisions, then the question of 'should we invest now' for augmentation is just as important as long term planning based on portfolios of potential investments".

The fit-for-purpose perspective is not well articulated in the HARC report. Its inclusion will help guide recommendations that go the heart of the matter, namely is the yield approach fit-for-purpose, and, if not, what needs to be changed.

### 2.1.2 A Technical Critique of the Yield Approach

Kuczera et al. (2023) compared the yield approach against an alternative long-established methodology called dynamic simulation. Here the key ideas and findings of that study are summarized.

The yield approach simulates a hypothetical steady state where demand and climate are stationary (that is, do not change statistically over time). Its use as a tool to identify the timing of interventions is based on the implicit assumption that as demand and climate change, the steady state adequately approximates drought security risk at every instant of time.

Any dynamic system with inertia will resist a change in forcing (or disturbance) and therefore take a finite time to respond to the change. In the case of a water resource system, the inertia can be represented by the ratio of storage and demand for a given streamflow resource - the bigger the ratio, the more slowly the system responds to disturbance. If the rate of change in demand and climate is faster than the inertial response, the system will never reach the steady state assumed in the yield approach. Kuczera et al. (2023) show that applying the yield approach in such circumstances runs the risk of mis-specifying the timing of interventions and mis-specifying actual drought risk.

The appeal of the yield approach comes primarily from the intuitive way the timing of interventions is presented - see Figure 1. The intuition works like this: Whenever yield drops below demand, the system is no longer secure requiring an intervention to boost yield. If demand is below yield, the system is secure.

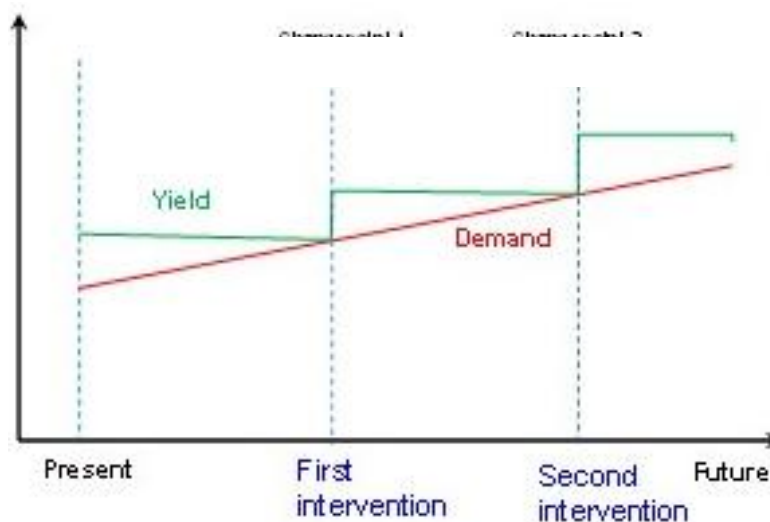


Figure 1. Demand-yield diagram for a stationary future climate.

On both counts, this intuition is wrong for systems with significant inertia.

Kuczera et al. (2023) provide an example involving growing demand and drying climate in which the yield approach requires an immediate intervention even though the system is 74% full. The yield approach cannot make allowance for the fact that system is currently 74% full and therefore in the near future has a security that exceeds the minimum acceptable level. In fact, the first intervention can be delayed eight years while still maintaining an acceptable level of security. In this example, the investments recommended by the yield approach are 50% greater in present worth terms (5% discount rate) than the investments recommended by dynamic simulation.

Likewise, during an extreme drought, the short-term security risks could be catastrophic even though yield exceeds demand. This situation occurred in the Sydney system circa 2007 when storage levels reached 35% and the decision to construct the Kurnell desalination plant was made.

The root of the problem is that the yield approach hides important information from decision makers. It fails to communicate how actual risk-based security metrics evolve over time.

Kuczera et al. (2023) concluded for systems with considerable inertia and subject to significant non-stationary forcings, that the default approach for evaluating system performance should be dynamic simulation. From a technical perspective, the yield approach uses an invalid model of system dynamics. This is not an opinion but a technical fact. It is important this be communicated correctly.

### *2.1.3 Should the Yield Approach Be Abandoned?*

As the Sydney system has large inertia, the above critique of the yield approach would suggest it has no legitimate role. In the reviewer's opinion, yield retains a useful role in guiding long-term planning. While it cannot support investment business cases, it can provide, for relatively little effort, an insightful framework for understanding how the system needs to evolve over the long term to cope with growing demand and climate change.

This type of analysis is based on snapshot (or time-slice) scenarios which represent system steady states at different times in the future. Figure 2 conceptually illustrates yield snapshot scenario modelling used in the Sydney 2017 water plan and recently for the SEQ grid. Each point in Figure 2 shows the minimum cost solution (or portfolio) of assets and operating rules that satisfies yield security criteria for a given level of demand and climate in a particular future year. This type of analysis using cloud-based optimization is much more capable and cost effective than expensive manual trial-and-error search.

For each point in Figure 2 there is a specific system configuration describing new assets and changes in operating rules. One can then get insight into how the system will need to evolve to cope with growing demand and changing climate. It identifies options that will be needed in the future.

Unfortunately, the pathway from one solution to the next is not necessarily consistent because the optimization is conducted independently for each selected year. The solution in year  $t$  may contain assets that are not present in the solutions for later years.

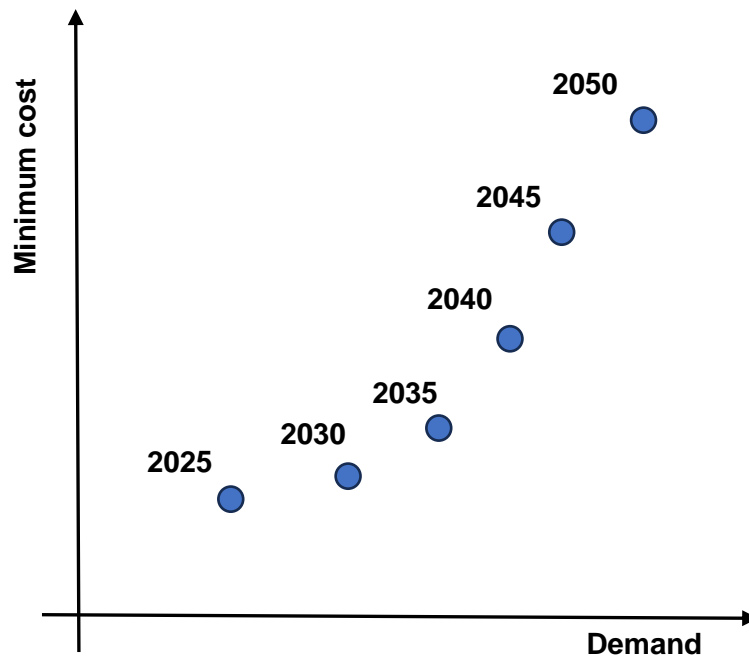


Figure 2. Snapshot scenario modelling using yield approach.

#### 2.1.4 Dynamic Simulation and Optimization to Build Investment Business Cases

The yield approach is conceptually the wrong method to determine the timing of the next intervention or, more generally, a schedule which describes which future actions to implement and when to implement them.

Dynamic simulation is the correct method. Starting at the current storage, it tracks the future performance of the system using multiple replicates of future changing climate and growing demand. Intervention is required when performance falls below an acceptable level.

The yield approach can be seen as special case of dynamic simulation where future climate and demand are stationary (or statistically unchanged over time). Figure 3 illustrates a dynamic simulation under stationary conditions. It shows two trajectories of a risk-based level-of-service (LoS) metric. The solid black trajectory corresponds to a low starting storage, while the dashed trajectory corresponds to a high starting storage. Once the memory of the starting storage fades, the trajectories converge to the same steady state. The steady-state metric corresponds to the yield LoS metric. Unless the inertial response time is very small, the steady-state metric cannot represent the actual risk trajectory faced by a system subject to nonstationary demand and climate.

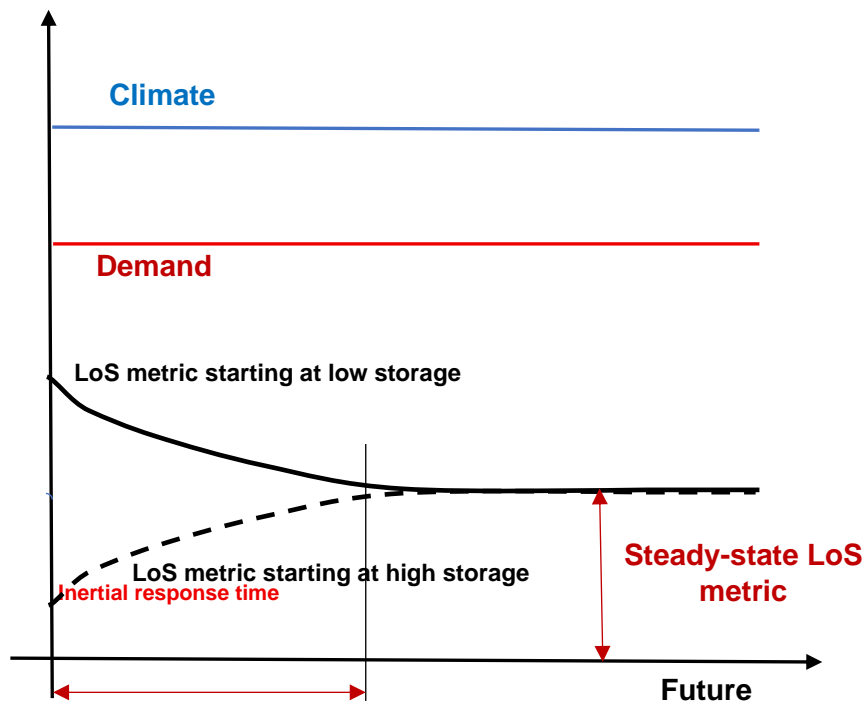


Figure 3. Dynamic simulation under stationary climate and demand

Figure 4 illustrates how the timing of the next intervention is determined using dynamic simulation. It shows a growing demand (red line) and drying climate (blue line). Without any intervention, performance will deteriorate as availability of surface water declines and demand grows. Dynamic simulation tracks one or more risk-based level-of-service (LoS) metrics (solid black line). When any of these metrics cross the maximum acceptable value (red dashed line), an intervention is required. Allowing for lead time, intervention starts at the time shown by the blue arrow. The dashed black line shows the short-term recovery in the LoS metric after intervention followed by a return to deteriorating performance as demand and climate continue to change.

This process is considered very intuitive and does not require a deep technical knowledge of the mechanics of dynamic simulation. It is difficult to understand why in HARC Table 4.4 this process is described as difficult to communicate. Figure 4 is no less compelling and intuitive than HARC Figure 4-1 but has the redeeming feature of being conceptually correct.

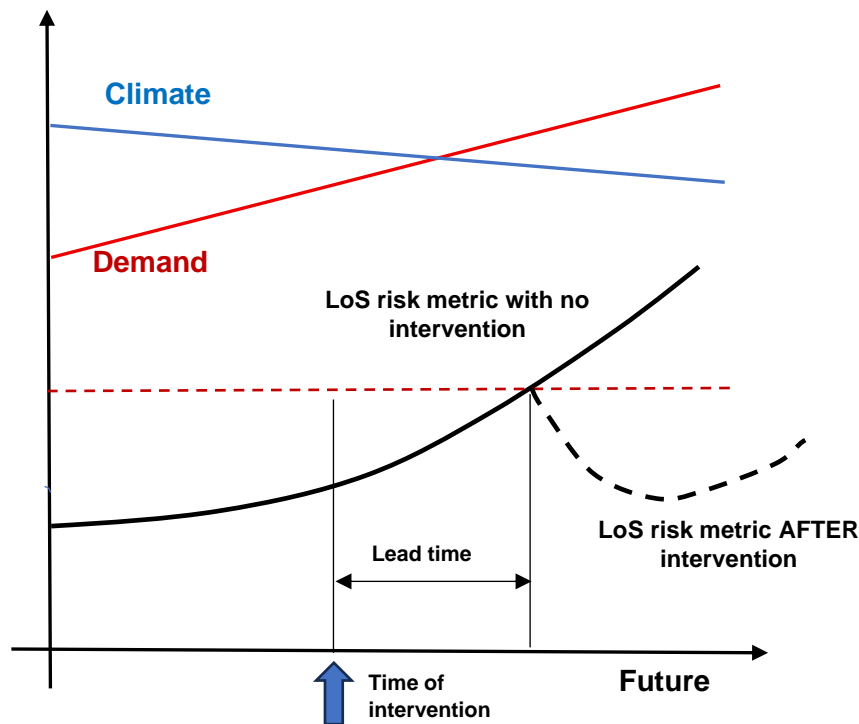


Figure 4. Timing of next intervention using dynamic simulation

## 2.1.5 Sydney 2024 WATHNET Model: What It Can and Cannot Do

### 2.1.5.1 Dynamic simulation

The review of the Sydney 2024 WATHNET model showed it can perform yield and dynamic simulation runs. Specifically, in system setting table 16, the flag in row 8, column 1 allows the user to select yield or dynamic simulation. When selecting dynamic simulation, one of the demand scenarios provided by Sydney Water must be selected from tables 45 to 47.

In the case of dynamic simulation, the 2024 model needs the following enhancements to be suitable for informing a business case about the timing of next intervention:

1. Scripts to track the evolution of performance metrics over the simulation period.
2. Scripts to track present worth operating costs and capital costs of interventions.

Both of these tasks are straightforward and involve low effort.

Tracking costs in real time within WATHNET is strongly recommended. It is much safer and more efficient than post-processing.

### 2.1.5.2 Yield simulation

In the case of a yield simulation, the most efficient procedure is to simulate one very long record (say  $10^6$  years). Memory of the initial condition is forgotten within a decade or so, allowing virtually all of the record to track steady-state performance. Such a simulation can be efficiently done in console mode. In GUI mode, graphical visualization of long time series is not practicable. For this reason, multiple replicates are used with storage at the end of one replicate carried over to the start of the next replicate.

### 2.1.5.3 Optimization of Options Space

The WATHNET software supports high-level multi-objective optimization, which is very well suited for optimizing minimum cost schedules of future intervention that maintain an acceptable level of security. This is a proven capability. A few comments are made to motivate its practical value.

The options space in urban water management is very large and complex. It not only includes infrastructure options that augment supply or reduce demand but also operating rules. Finding the best combination of infrastructure and operating rules is not a trivial task. The traditional approach is to use a trial-and-error search guided by experience and intuition.

In problems such as urban water managements where there is a consensus on objectives (eg minimize cost) and constraints (eg maintain acceptable LoS), optimization offers a much faster and more cost-effective way than trial-and-error to screen out inferior options to produce a set of “promising” options for planners and decision makers to explore in detail.

It is not widely appreciated that operating rules need to be changed to get the best outcomes from new infrastructure. Mortazavi et al. (2012)<sup>1</sup> illustrate the importance of optimizing both infrastructure and operating rules in a case study for the Sydney system supplying a not-so hypothetical population of 7 million. Figure 5 taken from Mortazavi et al. (2012) shows two Pareto fronts: In scenario 1, two infrastructure options and one operational decision (the new desalination trigger) were optimized; in scenario 2, two infrastructure options and all seven operational decisions were optimized. The differences are sobering and highlight the importance jointly optimizing infrastructure options and operating rules.

The options space in this example is relatively small but nonetheless impressive. If there were ten possible values for each decision, there would be  $10^9$  possible combinations. Given there usually is strong interaction between sets of decisions, trial-and-error search, even if informed by intuition and experience, is unlikely to find the “good” options.

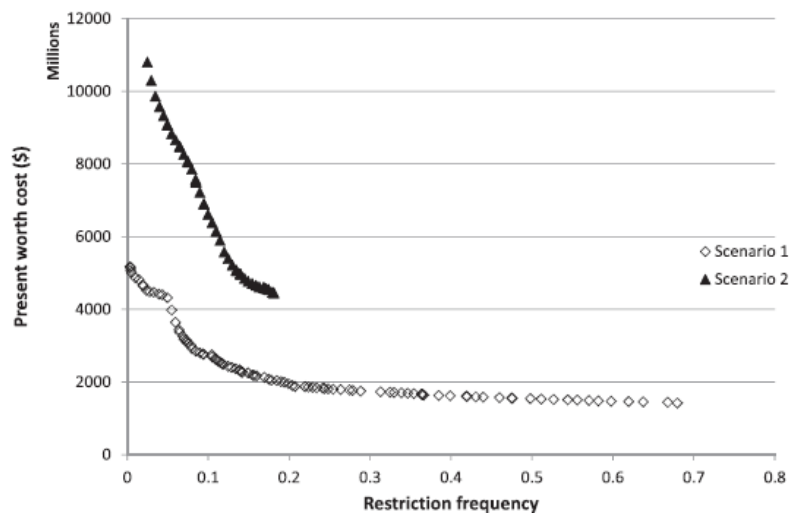


Figure 5. Two Pareto fronts illustrating the consequence of not optimizing infrastructure options and operating rules jointly: Scenario 1 optimizes two infrastructure options and one operational decision; scenario 2 optimizes two infrastructure options and seven operational decisions [taken from Mortazavi et al. (2012)].

<sup>1</sup> Mortazavi, M., G. Kuczera, and L. Cui (2012), Multiobjective optimization of urban water resources: Moving toward more practical solutions, *Water Resour. Res.*, 48, W03514, doi:10.1029/2011WR010866.

### *2.1.6 Suitability of Level-of-Service Criteria*

The operating licence specifies three LoS criteria that must be satisfied when determining yield. Two of the criteria, robustness and reliability, are consumer-focused in the sense they directly describe impacts on consumers.

The third criterion, security, is not consumer-focused but represents a storage state of near-emptiness. This criterion is synonymous with “running out of surface water”. Simulations of extreme drought have shown that the empty state and near-zero supply can persist for extended periods of the order of a year. In a system without climate-independent supply, such periods would represent an existential threat to Greater Sydney – options such as carting water from other drought-ravaged regions are unviable. A key weakness of the near-emptiness security criterion is that it does not consider the duration of empty state events - being empty for one month is dramatically different to being empty for eighteen months.

The Greater Sydney system can guarantee a climate-independent supply up to 250 ML/day, which is about 15% of current consumption. As a result, the consequences of running out of surface water for extended durations are no longer clear. A more meaningful representation of security is needed.

A more relevant approach would focus on the conditions under which Greater Sydney is no longer a viable place for its inhabitants. In principle, one could define the minimum viable supply MVS that represents the supply where sustainment of urban function and a minimum acceptable level of economic activity can just be maintained. This is a much more relatable security metric than the current near-emptiness metric, one that policy makers and the general public would be expected to understand intuitively.

If one moves to a MVS-based security criterion, the next question to be answered is, what is a tolerable risk of failing to deliver MVS over different durations? Should the risk be zero on the grounds that MVS should be a fundamental guarantee for a modern urban area or should it be finite? If a finite likelihood is tolerated, how is an existential threat to Greater Sydney valued? A very low likelihood, catastrophic consequence event that does not fit comfortably with expected present worth cost calculus.

With a MVS perspective, the thinking focusses on the spectrum of failure-to-supply impacts. The existing robustness and reliability metrics focus on the event that restrictions occur regardless of their severity. Noting there are major economic and social differences between level-one and level-five restrictions, it is reasonable to ask whether LoS criteria should address intermediate impacts between the soft bookend of experiencing any kind of restrictions and the harsh bookend of operating at MVS for extended duration.

To be complete, a review of the operating licence should include a reassessment of LoS design metrics and criteria. The choice of security metrics and criteria is much more likely to have a profound impact on the water system investments than choice of methodology. At a minimum, it is recommended that agencies and stakeholders involved in water security should reassess LoS in the same cycle as review of the operating licence.

### *2.1.7 Revising the Operating Licence*

Given that the yield approach is not suitable for developing a business case for interventions to maintain an acceptable future LoS, the operating licence is in need of revision.

It is recommended that the revised licence should not be prescriptive about methodology, instead requiring that best practice be used. This would acknowledge the fact that best practice evolves over time in response to feedback and innovation. This is particularly important now that climate change impacts need to be taken into account. The considerable uncertainty about climate change impacts feeds into uncertainty about what is the best decision-making paradigm.

It makes sense that the licence focus on performance metrics deemed important by government and stakeholders and on defining thresholds for tolerable performance. This is the most consequential element of the licence. It will most likely involve making difficult economic and social trade-offs.

## 2.2 Drought Contingency Plan

The Greater Sydney Drought Response Plan (GSDRP) published in January 2026<sup>2</sup> appears to be the official document describing drought response. As the drought response plan has a major influence on the yield, it would make sense for the HARC review to use the GSDRP as the basis for gauging the adequacy of the drought response built into the WATHNET model.

While the GSDRP relies on restrictions, ramping up desalination and Shoalhaven transfers, the process by which these actions are triggered is not entirely clear. The GSDRP states that there are several primary indicators to inform decision-making processes (eg, recorded rainfall in catchments, recorded inflows to storages, predicted time to reach 15% storage level in a hypothetical drought; and water quality analytes that affect treatment) and secondary indicators (eg observed storage depletion rates and BOM's climate driver updates that include rainfall projections and El Niño/La Niña outlooks).

As the WATHNET model only uses storage triggers, there may be a significant mismatch between the GSDRP and the WATHNET model's drought response.

Of concern is the fact that there is no plan for extreme drought measures. It appears such a plan will eventuate when the system storage falls to 40%, at which time "the DEC to advise the Minister and Cabinet on further demand restrictions and other measures". If the drawdown experienced in the Tinderbox drought were repeated, it would take about 2 years to drop from 40% to empty unless draconian measures to reduce consumption were implemented.

Two additional observations are made:

1. HARC recommend exploring the concept of reserve storage. It would help if this concept were contextualized within the current drought contingency framework and how the reserve storage fits in with the near-emptiness LoS security criterion.
2. HARC recommend the concept of working with restrictable and unrestrictable demand. This makes much sense. However, in extreme drought, even unrestrictable demand can be targeted by extreme measures such as pressure reduction or supply cutoff.

## 2.3 System Representation

### 2.3.1 Representation of Demand Zones and Transfer System

The stakeholder response from Sydney Water raised concerns about the ability of the system to supply demand when storage drops below 30%. The GSDRP refers to high risk nodes in extreme

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<sup>2</sup> <https://www.sydneywater.com.au/content/dam/sydneywater/documents/greater-sydney-drought-response-plan.pdf>

drought. These concerns raise an important question, does the WATHNET model adequately represent the transfer system and demand zones?

There is a striking difference when comparing the Sydney WATHNET model with the models for Perth and SEQ. Relatively speaking, the Sydney model has significantly fewer demand nodes and a far simpler representation of the bulk transfer system.

The reviewer does not have the detailed system knowledge to comment on the adequacy of the transfer and demand representation in the current WATHNET model. However, there are two principles which should guide representation of demand zones and transfer system:

1. Explicitly represent capacity limits on all current and future bulk transfer arcs. A demand shortfall may occur if there is insufficient supply or if there are transfer constraints. In the latter case investments will be needed to avoid such shortfalls. In the Perth and SEQ systems, investment in the future transfer system represents a large part of the capital program.
2. Ensure that the bulk transfer arcs supplying a demand node can physically deliver water to whole physical region represented by the node. If this is not the case, then more granularity is needed. This issue is particularly important in demand zones that experience high growth and when adding climate-independent supplies such as desalination which may only serve a limited demand zone.

Given that Greater Sydney is experiencing significant population growth and changes in development policy, it makes sense that this representation be regularly reviewed and documented by multi-agency experts to ensure the WATHNET model adequately represents the system in its current state and in all possible augmented states.

### *2.3.2 Water Quality*

The stakeholder response from Sydney Water also raised concerns about the impact of source water quality on the ability to supply water from affected sources. While it is not clear why this is out of scope, the issue nonetheless needs follow up. The current WATHNET model does not deal with water quality events that impact supply. As a result, it is not known how much such events impact on security of supply.

The WATHNET framework can handle stochastically-generated water quality events that affect supply. For example, if a source is assigned a poor water quality, it can be made unavailable until water quality improves. The linear program in WATHNET will then reassign supply from different sources according to their water values. Alternatively, blending rules may be imposed to guide the linear program.

The main task is to develop a stochastic model of poor water quality events that are correlated with hydroclimate inputs. The most flexible approach would use the nearest neighbour algorithm built into the harvest node to describe observed or modelled events.

## 3 Climate Change Impact Assessment

### 3.1 Climate Change Approaches

#### 3.1.1 Streamflow Covariate Approach

To date, WaterNSW has calibrated stationary stochastic models to streamflow. Kiem et al. (2021)<sup>3</sup> have shown that the historical inflow time series for Warragamba, Avon and Shoalhaven catchments are not stationary. This was done by performing a split-sample test using 1990 as the split year. Stochastic models calibrated to pre-1990 data significantly overestimated post-1990 flows. Kiem et al. then showed that adding a temperature covariate to the stochastic model (annual average maximum air temperature at Bathurst) produced a satisfactory split-sample test.

There are two implications of this work:

1. It suggests that climate change has already affected the historical record. The stationary stochastic model overestimates present-day streamflow and hence system yield. As a result, WaterNSW should no longer default to a stationary stochastic model when fitting to historical streamflow data.
2. The temperature covariate offers a simple way to project future climate change – see Kiem et al. (2021). For selected emission pathways, NARcliM can provide temperature projections for the Bathurst site. Uncertainty in the temperature covariate parameters can be used to communicate uncertainty in future streamflow trajectories.

#### 3.1.2 NARcliM Rainfall-Runoff Approach

This is the approach that is the primary focus of the HARC review. It is largely consistent with past WaterNSW practice and the NSW government’s Common Planning Assumptions. It uses NarcliM to generate multiple climate time series that are representative of the climate change for a particular emissions pathway. These time series can be post-processed using the Schaake shuffle to preserve temporal and spatial dependence. The rainfall and potential ET time series are then input to the calibrated Sacramento rainfall-runoff models to generate runoff.

HARC supports “WaterNSW’s current position that the current rainfall-runoff models are not suitable to apply directly in climate change impact assessment and should only be used to calculate change factors to apply to other datasets”. The change factors are used to scale inflow time series presumably stochastically generated.

Implicit in the scaling of stochastic data is the assumption that the stochastic data is representative of the NarcliM reference period. Given that observed inflow time series for Warragamba, Avon and Shoalhaven have been shown to be nonstationary, the logical approach would be to use the stochastic covariate model to generate streamflow with temperature representative of the reference period.

### 3.2 Pros and Cons

Two issues with the NARcliM approach deserve mention.

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<sup>3</sup> Kiem, A. S., Kuczera, G., Kozarovski, P., Zhang, L., & Willgoose, G. (2021). Stochastic generation of future hydroclimate using temperature as a climate change covariate. *Water Resources Research*, 56, 2020WR027331.

The first arises from its dependence on the Sacramento rainfall-runoff model to transform rainfall and potential ET into runoff. The Sacramento model is not capable of representing climate change impacts on vegetation water use arising from increasing CO<sub>2</sub> fertilization and temperature. Recent work has shown widespread increases in NDVI over much of eastern Australia. Rifai et al. (2022)<sup>4</sup> conclude that CO<sub>2</sub> fertilization has outpaced growing aridity to drive greening of Australian woody ecosystems. Between 1982–2019 they show median NDVI has increased (11.3 %) across 90% of woody regions. In a catchment where 10% of rainfall becomes runoff, a 1% increase in catchment water use translates into a 10% reduction in runoff. Even though the Sacramento model may be calibrated to the recent past, it does not address its fundamental shortcoming in representing climate change induced changes to catchment water use. There is a distinct possibility that the change factors will be underestimated using this approach.

Finally for a given emissions pathway, NARClIM rainfall trajectories generated by different climate models can be divergent with some favouring wetter futures and others favouring drier futures. Such large variability especially in the medium to far future, presents challenges for strategic planning as it is difficult to adapt when trajectories are largely unknowable.

The main strength of the streamflow covariate approach is that it is data-driven. While the lack of physics in the model may be seen as a major weakness, the data-driven association between temperature and streamflow is nonetheless real. One would expect the NARClIM approach to be consistent with this historical association.

Projecting this association into the future rests on the assumption that the mechanism driving the historical association remain valid under a future warming climate. One would expect, in the absence of tipping points and strong nonlinearities in climate dynamics, that the historical association will be representative of the near and possibly medium future. Interestingly the pattern scaling derived from NARClIM shown in HARC Figure 4 suggests a linear decline in Warragamba rainfall as a function temperature increases over the period 1976 to 2089. This offers a physics-based support for the linear association identified in the covariate approach. As an aside, this result does make it puzzling why HARC has downplayed the streamflow covariate approach in preference to the NARClIM approach using pattern scaling.

### 3.3 A Joint Approach is the Safest

The NARClIM approach is deeply embedded in NSW government and its agencies. It, therefore must be used. However, the analysis in the previous section shows there are sound reasons for WaterNSW to keep the covariate approach.

At a minimum, the covariate approach will be needed to generate stochastic data representative of the NARClIM reference period. However, the covariate approach offers an independent and data-driven method to project future streamflow trajectories and in doing so provides a check on the NARClIM approach. In the view of the large uncertainties in projecting future climate change, this seems a sensible strategy.

Figure 6 illustrates how these approaches can be used jointly. The blue line shows the historic flow (taken to be a statistic such as median) trajectory estimated by the covariate approach. The solid and dashed blue lines correspond to the covariate projected flow and uncertainty using a NARClIM-

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<sup>4</sup> Rifai, S. W., De Kauwe, M. G., Ukkola, A. M., Cernusak, L. A., Meir, P., Medlyn, B. E., & Pitman, A. J. (2022). Thirty-eight years of CO<sub>2</sub> fertilization has outpaced growing aridity to drive greening of Australian woody ecosystems. *Biogeosciences*.

based temperature trajectory. The solid and dashed red future trajectories correspond to the NARCLiM projected flow and uncertainty for the same emissions trajectory.

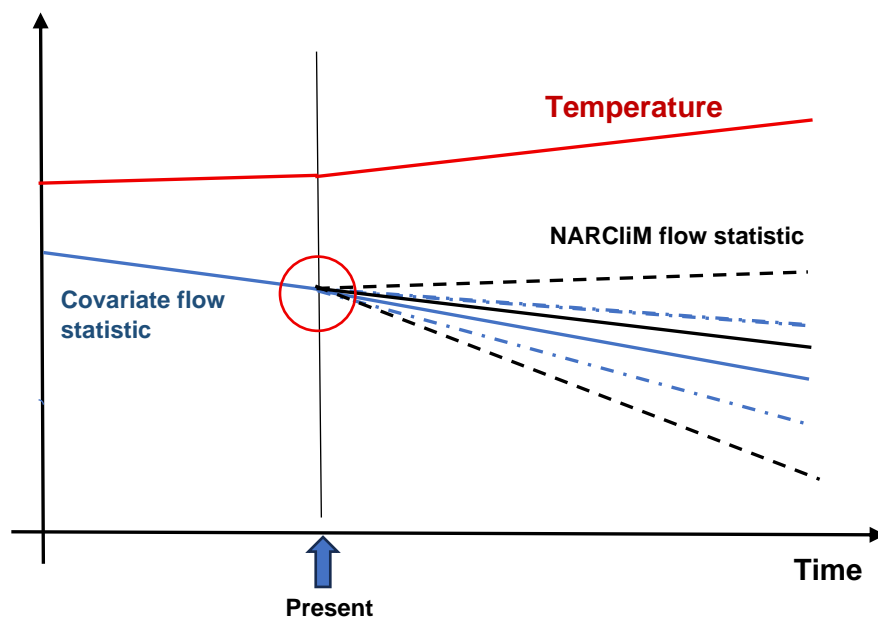


Figure 6. Future flow trajectories based on NARCLiM and covariate approaches.

On reflection the joint approach offers helps build confidence in climate change projections in several ways:

1. Given that the covariate trajectory is data -driven, the future NARCLiM trajectory should start in the same location as the future covariate trajectory. In other words, the trajectories should start inside the red circle. If they do not, the source of the inconsistency needs to be resolved.
2. Given that the NARCLiM-based pattern scaling suggests a linear relationship with temperature, one would expect the NARCLiM and covariate uncertainty intervals to be consistent at least in the near and medium futures.
3. Blending may help reduce uncertainty. If, as shown in Figure 6, the covariate uncertainty is narrower than the NARCLiM uncertainty, one may assign higher likelihoods to the trajectories within the covariate interval. Likewise, if NARCLiM uncertainty were narrower, higher likelihoods would favour the NARCLiM trajectories.

## 4 Historical and Stochastically Generated Hydrology data

### 4.1 Provenance of “Observed” Streamflow Data

WaterNSW has produced long historical streamflow records extending back to 1909. Long streamflow records are incredibly valuable for two reasons. First, streamflow is the primary input to the stochastic model. Second, because streamflow integrates climate forcing and catchment response, a long quality record provides a valuable opportunity to detect change in catchment response arising from climate change. The integrity of the yield assessment and business cases

based on the WATHNET model is critically dependant on the integrity of the streamflow record that is used to calibrate stochastic model.

The HARC report’s emphasis on rigorous provenance is strongly endorsed. Any issues or shortcomings with the provenance of the data need to be assigned the highest priority.

The WaterNSW streamflow data is a composite of methods including gauging, reservoir water balance, rainfall-runoff modelling, regression and transposition. These methods have different skill levels which can potentially create inconsistencies and problems for the calibration of stochastic models.

**Figure A2-1 Summary of Inflow Derivation (updated from SKM, 2003)**

Inflow	1909	1915	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2007
Warragamba	G	G	G	G	G	G	W	W	W	W	C	C	C	C	C	C	C	C	C	C
Wingecarribee	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Tallowa	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Fitzroy Falls	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Nepean	R	R	R	R	R	W	W	W	W	W	C	C	C	C	C	C	C	C	C	C
Avon	R	R	R	R	W	W	W	W	W	W	C	C	C	C	C	C	C	C	C	C
Cordeaux	R	R	R	W	W	W	W	W	W	W	C	C	C	C	C	C	C	C	C	C
Cataract	W	W	W	W	W	W	W	W	W	W	C	C	C	C	C	C	C	C	C	C
Woronora	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Penrith	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	T
Pheasants Nest	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
Broughtons Pass	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T

T Transposed flow     
 R Regression     
 H Rainfall runoff model (HSPF)  
G Recorded pre-dam flow     
 W Unknown water balance     
 C Water balance (CMCR)

#### 4.1.1 Objective Functions and Time Scales

The stochastic model in WATHNET uses a two-level hierarchical model. At the top level, a multi-site probability model is calibrated to seasons. At the second level, a kNN algorithm is used to disaggregate the seasonal volume into monthly volumes. WaterNSW currently uses one 12-month season based on the calendar year to calibrate the top-level model.

This provides insight as to the type of objective function that should be used to calibrate rainfall-runoff or regression models used to reconstruct runoff:

1. For the level-one stochastic model, the primary need is for annual flow estimates to be unbiased with minimum error. Given the errors are likely to be normally distributed, a least squares objective function (which is optimal for normally distributed independent errors) coupled with a bias penalty seems appropriate.
2. For the level-two disaggregation, the primary need is to correctly estimate monthly patterns. This suggests one component of the objective function be based on minimizing errors in monthly fragments.

#### 4.1.2 Reservoir Water Balance CMCR

CMCR is used to estimate flows for five catchments (including Warragamba) since 1960. CMCR estimates are considered more accurate than rainfall-runoff based methods and, therefore, should be the default choice where possible.

HARC notes issues with the treatment of negative flows and recommends, though not formally, that methods based on using a reference gauge be used to adjust flows.

As CMCR will continue to be used into the foreseeable future, it seems a wise investment for WaterNSW to update its CMCR approach using best practice for correcting negative flows in historic records and in future applications.

#### 4.1.3 Rainfall-Runoff Methods

HARC recommends that the Sacramento model be applied to reconstruct estimates originally derived using HSPF. This represents a timely opportunity to ensure a consistent and well documented approach is applied to catchments that rely on rainfall-runoff derived flow estimates.

However, in view of the accuracy needs stated in Section 4.1.1, it remains to be seen whether the Sacramento model will give the best return for effort. The Sacramento model is overparameterized with 16 parameters requiring calibration. This means that calibration to daily flows is unlikely to produce well defined parameter estimates.

Three simpler options<sup>5</sup> are available:

1. For annual flows, a regression model may do as well, if not better than, the Sacramento model particularly if the Sacramento objective function fails to put enough emphasis on annual flows.
2. For monthly flows, there are two parsimonious models, WAPABA and abcF, that perform well and are simple to calibrate.
3. For daily flows, the four-parameter GR4J is known to perform very well and is simple to calibrate.

As Tallowa is the largest of the catchments relying rainfall-runoff estimates and key to the Shoalhaven interbasin transfers, it makes sense to compare the Sacramento model against the three simpler options before deciding on preferred models.

#### 4.1.4 Stationarity of Rainfall-Runoff Response

The deeper problem with traditional rainfall-runoff models is the assumption of stationarity in rainfall-runoff response. There is now considerable evidence in eastern Australia that stationarity is not preserved in many catchments with research ongoing as to the causative factors.

The practice of calibrating rainfall-runoff models to the recent past circumvents this issue to some degree if the model is used to estimate runoff using rainfall representative of the near future. However, this does not resolve the problem when reconstructing runoff well before the period of calibration.

Split-sample testing is necessary to check for stationarity in rainfall-runoff response. However, before undertaking such a test, it is important to ensure historic rainfall and potential ET records are free of artefacts that may manifest as non-stationarity. HARC's recommendation to use quality-

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<sup>5</sup> GR4J, WAPABA and abcF functions are available in WATHNET model and can be calibrated within WATHNET using SCE or robust Gauss-Newton methods

assured gauged rainfall instead of gridded rainfall is strongly endorsed. Gridded rainfall is based on gauged rainfall networks whose coverage declines as we move back in time. This poses a real risk of introducing inconsistency into the record.

That said, the issue of declining gauge coverage has to be managed with gauged networks. If a rainfall-runoff model is calibrated to say a three-gauge network, it cannot be used without some kind of correction to reconstruct runoff when the network shrinks to one gauge. At a minimum, a correction needs to be applied to the one-gauge rainfall to force some form of consistency with the three-gauge network. Alternatively, the rainfall-runoff model can be calibrated to the single gauge at the expense of reduced performance.

When a split-sample test is conducted, it useful to have diagnostics that provide insight as to why the test fails. Brieva et al. (2025)<sup>6</sup> illustrate how Bayesian methods can be used in split-sample testing. Using the abcF monthly rainfall-runoff model in two Shoalhaven catchments they present two diagnostics. The first is the traditional time series plot comparing observed flows in one period against predicted flow and prediction limits using parameters from the other period. The second is a posterior plot of differences in parameters derived from different calibration intervals. This plot helps identify which parameters are responsible for the non-stationarity. This approach is quite robust at the monthly scale for well-behaved rainfall-runoff models but is expected to be unworkable for the overparameterized Sacramento model.

There is not much precedent on what to do if significant non-stationarity is detected in the rainfall-runoff response. Some difficult judgements need to be made. It may be necessary to settle for a shorter reconstruction for which there is higher confidence the rainfall-runoff model reliably represents the rainfall-runoff response. As the stochastic model in WATHNET can accommodate records of different length in calibration, this option can make use of the reduced but reliable information.

## 4.2 Stochastic Model

The primary application of the “observed” streamflow data is calibration of a stochastic model to generate hydroclimate replicates for yield and dynamic simulation runs. There are several issues arising from the HARC report regarding use of stochastic model that deserve mention.

### 4.2.1 Stationarity and Covariate Stochastic Model

WaterNSW has used stationary stochastic models of streamflow. The assumption of stationarity should no longer be the default assumption. It needs to be checked using split sample tests<sup>7</sup>.

As Kiem et al. (2021) have shown, the Warragamba, Avon and Shoalhaven records do not pass split-sample tests based on split year 1990, which corresponds to the beginning of a clear trend in warming temperatures.

As it is expected split-sample tests will fail using a stationary model, it seems inevitable that WaterNSW will need to resort to temperature covariate stochastic models and confirm they pass split-sample tests.

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<sup>6</sup> Brieva, C. et al. (2025) Accounting for Non-Stationarity in Streamflow using Vegetation-Aware Rainfall-Runoff Models in Greater Sydney Water Supply Catchments. The University of Newcastle and the University of Technology Sydney.

<sup>7</sup> It is noted that the WATHNET stochastic model has built-in support for split-sample testing.

### 4.2.2 Yield Runs

Generating multiple replicates for yield runs needs care.

In WATHNET, the only safe multi-replicate approach is to generate **one** long stochastic record (say  $10^6$  years) and cut it into equal length replicates. This ensures the persistence in the stochastic data at the end of the replicate is carried over to the next replicate along with storage.

If WATHNET is used to generate say 10,000 100-year replicates, this is not equivalent to one 1,000,000-year record. This is because the stochastic model was designed to support dynamic simulation. As a result, it uses the same antecedent conditions for each replicate. If such replicates are used in a yield run, the first part of the replicate (long enough to lose memory of initial conditions) must be ignored when tracking performance. This is less efficient and more convoluted than the preferred method.

### 4.2.3 Disaggregation

The stochastic model in WATHNET uses a two-level hierarchical model. At the top level, a multi-site probability model is calibrated to seasons. At the second level, a kNN algorithm is used to disaggregate the seasonal volume into monthly volumes.

WaterNSW currently uses one 12-month season based on the calendar year to calibrate the top-level model. The kNN disaggregation is therefore required to disaggregate annual volumes into 12 monthly volumes.

HARC notes that the practice of using nearest-neighbour disaggregation ( $k$  set to 1) limits the variability of monthly sequences in extreme drought. HARC's advice to explore larger values of  $k$  makes good sense but may result in significant shifts in yield if the near-emptiness LoS metric is binding.

The kNN algorithm uses a rank-based trapezoidal distribution when sampling a representative historical record when  $k > 1$ . It therefore is worthwhile to confirm the reasonableness of using  $k > 1$  with 12-month seasons using an "independent" method. One such method involves splitting the calendar year into multiple seasons (say two 6-months seasons, three 4-month seasons) and calibrating the top-level model to multiple seasons. This will introduce more inter-seasonal variability and reduce the role of the kNN algorithm to disaggregating 4 or 6-month volumes into monthly values rather than 12-month volumes. It is important that, whatever seasonal split is adopted, the level-one stochastic model preserves multi-year persistence.

### 4.2.4 Paleo-Informed Stochastic Model

HARC notes that DCCEEW's stochastic model which underpins the NSW Treasury Common Planning Assumptions uses paleo-informed long-term persistence. This paleo-informed stochastic model has three hierarchical levels. The top-level is based on an alternating sequence of IPO positive and negative epochs whose length is sampled from a gamma distribution whose parameters are informed by paleo methods that reconstruct IPO epochs before the instrumental record. The second level then samples annual values from a multi-site autoregressive model conditioned on the IPO epoch (either wet or dry). The next level then disaggregates annual values.

The WATHNET stochastic model supports this framework which was tested for the Sydney system by Zhang (2019)<sup>8</sup>. This allows WaterNSW to rapidly evaluate the paleo-informed framework using streamflow. This avoids the weakness in DCCEEW's method which relies on rainfall-runoff model to convert stochastic generated climate variables into runoff. If WaterNSW pursue this, reviewing Zhang's thesis is strongly advised. One of her findings was uncertainty of the paleo-informed parameters for the gamma distribution had little impact on risk-based security metrics. What did have a major impact was the uncertainty in the autoregressive model parameters for wet and dry IPO epochs – splitting the instrumental record into wet and dry IPO epochs effectively halves the number of samples to estimate parameters.

#### *4.2.5 Calibration Using Composite Data*

When a composite streamflow record consists of directly-estimated flow (using gauging or reservoir water balance) and flows estimated using a rainfall-runoff or regression model, there is risk of statistical inconsistency between the composite subsets. This arises because the rainfall-runoff or regression model only generates expected runoff. These models fail to reproduce the full variability in observed runoff – the lower the calibration skill, the more serious the misrepresentation of actual variability.

If the composite record can be divided into contiguous homogeneous subsets (for example, subset A CMCR, subset B rainfall-runoff), it is recommended that split sample testing using the covariate stochastic model be used to check whether the subsets produce statistically different parameterizations.

If such split-sample tests fail, a judgment needs to be made whether the failure of the test warrants further action. There is an established literature on what is called Bayesian data augmentation that can be applied in principle to composite records. This approach has seen little application in hydrological stochastic modelling with the closest being application of the EM algorithm to fill in missing data in multi-site autoregressive models. The main effort would be developing software to implement the data augmentation algorithm and developing a suitable probability model of the unexplained variability in rainfall-runoff or regression estimates of annual or seasonal flows.

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<sup>8</sup> Zhang, L. Pacific Decadal Variability: Uncertainties and Implications for Water Resources, PhD thesis, University of Newcastle, 2018.

# WaterNSW Greater Sydney WATHNET Model 2026 Independent Review – comments from Anthony Kiem

**ANTHONY S. KIEM**

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- Prepared for HARC Services Pty Ltd (HARC) have been engaged by WaterNSW to conduct an independent review of the Greater Sydney WATHNET model
- 5 May 2026

# 1. Introduction

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As per the engagement letter received from HARC Services Pty Ltd (HARC) on 9 April 2026, this my feedback on HARC's review of the WaterNSW Greater Sydney WATHNET model along with some recommendations for future improvements.

This feedback was prepared after attending the “WATHNET Model Review Expert Panel Workshop” on 21 April 2026 and after reviewing the following documents that were provided by HARC:

- NSW00097\_WATHNETReview2026\_HydrologyData\_Final\_v1\_ExpertPanel.docx;
- Water supply model review - stakeholder workshop - SW feedback.docx;
- WATHNET Water Supply Model Review 2026\_NSW Treasury workshop response\_20260306.docx;
- NSW00097\_WATHNETModelReviewReport\_f1.docx;
- NSW00097\_WATHNETReview2026\_ClimateChange\_Final\_v1\_ExpertPanel.docx;
- WATHNET Review- Hydrology Updates Memo.docx.

## 2. Comments from the “WATHNET Model Review Expert Panel Workshop” on 21 April 2026

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### 2.1 Hydrology session

1. Will recalibrating the rainfall-runoff models to extend inflow data back into early 1900s/late 1800s result in realistic flow simulations? How will it be validated?
2. What is being done to ensure the current (and updated) rainfall-runoff models capture non-stationarity that has occurred in recent decades, especially the different ways drought can affect rainfall-runoff relationships and resulting inflows?
3. What metrics will be used to ensure rainfall-runoff models are realistically capturing the things that are important (e.g. overall (i.e. on average at each location) and also site/location specific and during dry seasons/years/decades and wet seasons/years/decades)?
  - a. Need to choose these metrics carefully because a rainfall-runoff model that looks good “overall” may not be realistic at certain locations or at the wet or dry end or for extreme/rare events.
  - b. As per Fowler et al. (2022)<sup>1</sup>, a rainfall-runoff model that works well in one drought may not work well in another drought because the reasons for reduced runoff per unit rainfall are not always the same (i.e. all droughts are different). So rainfall-runoff performance metrics need to consider overall conditions, multiple/different drought-dominated periods and multiple/different flood-dominated periods.

### 2.2 Climate change session

1. Bias correction (and delta change factoring) only changes magnitude but other characteristics are critical for yield assessment (e.g. frequency, duration, seasonality, location of wet/dry epochs and also antecedent catchment conditions). Does pattern scaling also just change magnitude?
2. For the bias correction is it multivariate? How is coherence maintained across the different variables? For example, if you bias correct rainfall then how is it ensured that evaporation is also bias corrected such that the relationship between rainfall and evaporation is maintained?
3. Why is the DCCEEW climate reference period (1976-2005) different to the WaterNSW climate reference period (1996-2005)? Is it possible to get alignment?
  - a. The choice (and justification for that choice) of baseline is important. The critical thing is to make sure there is no double counting of climate change impacts (i.e. no overestimation or underestimation based on choice of baseline). So if the baseline period is Y1 to Y2 and projected climate change impacts are coming from climate models that

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<sup>1</sup> Fowler, K., Peel, M., Saft, M., Peterson, T. J., Western, A., Band, L., Petheram, C., Dharmadi, S., Tan, K. S., Zhang, L., Lane, P., Kiem, A., Marshall, L., Griebel, A., Medlyn, B. E., Ryu, D., Bonotto, G., Wasko, C., Ukkola, A., Stephens, C., Frost, A., Gardiya Weligamage, H., Saco, P., Zheng, H., Chiew, F., Daly, E., Walker, G., Vervoort, R. W., Hughes, J., Trotter, L., Neal, B., Cartwright, I., and Nathan, R.: Explaining changes in rainfall–runoff relationships during and after Australia's Millennium Drought: a community perspective, *Hydrol. Earth Syst. Sci.*, 26, 6073–6120, <https://doi.org/10.5194/hess-26-6073-2022>, 2022.

use a baseline that overlaps or precedes Y1 to Y2 then that needs to be considered (i.e. removed) when assessing future impacts.

4. Pattern scaling approach. What is the difference between the pattern scaling approach and the temperature-covariate approach (apart from source of the data used to derive the temperature-rainfall relationship). If there is no fundamental difference, then this should be more clearly communicated. If there are major differences, then it would be useful to see a more detailed comparison between the two approaches giving information on the pros/cons of each. How was it decided/determined that pattern scaling is “better” than the temp-covariate approach? What is the difference between the two approaches other than the data for one comes from climate models and the other comes from observed data? If the fundamentals behind both approaches are the same, then why is one “better” or “preferred” over the other?

### **3. Comments or suggested edits for the HARC review reports**

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#### **3.1 Comments on “Review of historical and stochastically generated hydrology data” report**

1. Several times in the report the word “providence” is used in relation to the source/history of data records but I think you mean “provenance”?
4. HARC recommendations in the table at the top of page 11 start at recommendation #6. Where/what are recommendations #1-5?
5. 2<sup>nd</sup> para in Section 5.3.1....”record to enable an validation” should be “record to enable a validation”.
6. Recommendation #30: What does “reasonably homogenous” mean? And are you sure we want to do this – shouldn’t you calibrate the stochastic model such that it captures as much hydroclimatic variability as possible (including changes to rainfall-runoff behaviour)? I am confused by this recommendation and am possibly misunderstanding something.
7. Recommendation #32: Yes, investigate prevalence of monthly temporal patterns for near average or wet years being applied to synthetic low years BUT also need to make sure that there are a variety of temporal patterns being applied to “low flow” years.....not just the same observed low flow year each time.

#### **3.2 Comments on “Review of climate change impact assessment” report**

1. In Table 1:
  - a. Recommendation #8: What period is NARCLiM output bias corrected to match? And what “observed” data is used as the target? And what are the sensitivities associated with different options for these two things?
  - b. Recommendation #11: Why SSP2-4.5? What variable/metric is used to determine what the “highest impact scenario” is?
  - c. Recommendation #12: Agree with checking climate model outputs at different rainfall locations but also need to check across different decadal time periods as well as the overall historical period. Just as climate model outputs can be realistic for some places but not others they can also be realistic for some time periods but not others (e.g. some climate models are better in drought dominated periods than wetter than average periods and vice versa and some climate models do a reasonable job at reproducing climate conditions average over the whole period of observed record but overestimate rain in dry periods and underestimate rain in wet periods). In short, climate model outputs need to be checked to ensure key characteristics are reproduced in both space and time.
  - d. Recommendation #21: Why is this ranked as “low” for likely impact on yield assessment?
  - e. Recommendation #21: I agree with this recommendation and the use of multiple lines of evidence and a wide range of plausible scenarios. The work recently completed by Independent Hydroclimate Science Expert Panel (IHSEP) for the Murray-Darling Basin

Authority (MDBA) gives details on how this recommendation could be addressed. See John et al. (2026)<sup>2</sup> and the three IHSEP reports at the bottom of <https://www.mdba.gov.au/publications-and-data/publications/2025-sustainable-yields>. I see the IHSEP work is referred to at the top of page 23 so that is good (I will just leave this comment here for completeness).

2. Table 2, 4<sup>th</sup> row, right column: the comment there that using annual temperature as a covariate is “less preferred for climate change projections compared to other available techniques”. Why? What is the difference between a temperature-covariate approach and the “preferred” pattern scaling approach? Aren’t they essentially the same approach and it is just that the approach described as the “temperature-covariate approach” derives the relationship between temperature and rain (or flow or whatever the target variable is) based on observations whereas the pattern scaling approach uses climate model outputs. Why is an approach that uses climate model outputs to derive the key relationships (i.e. the pattern scaling approach) preferred over an approach based on observed data (i.e. the temperature-covariate approach)? How do we know the relationships derived from the climate model outputs are “real”?
3. Table 2, 5<sup>th</sup> row, right column: “HARC’s view is that techniques that incorporate non-linear climate change trends over time (e.g. pattern scaling.....”. The temperature-covariate approach can do this as well and this is actually one of the main reasons why the temperature-covariate approach was developed. The way this is written could be taken as the pattern scaling approach is the only way non-linear climate change trends can be consider, which is potentially misleading.
4. Fig 3 and associated text: As pointed out in the text above Fig 3 this result is based on one climate model. Need to check whether this finding holds for other climate models.
5. Table 5: Need more details and clarity on how/why these reference periods were arrived at and if there is any special reason why the ones currently being used are different. It is recommended that effort is put towards getting the relevant organisations together and agreeing on a common reference period (or at least gaining an improved understanding about why certain reference periods are preferred by certain organisations/applications). It would be much more efficient, and easier for stakeholder/community consultation if there was a common reference period used for all climate change impact assessment across NSW. It is also recommended to consult with other organisations outside NSW, but that affect or could be related to NSW water resources management, to see what they are doing and try and align accordingly (e.g. Murray-Darling Basin Authority, Commonwealth Department of Climate Change, Energy, the Environment and Water’s National Climate Risk Assessment, etc.).
6. Fig 4: Is the temperature versus rainfall relationship show here statistically significant? What about at other locations? Are similar plots available for evaporation and is the temperature versus evaporation relationship statistically significant?

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<sup>2</sup> John, A., Young, W., Nathan, R., Cleugh, H., Westra, S., Guo, D., Danielle, K., Kiem, A.S. and Neal, B. (2026). Research and institutional priorities for assessing hydroclimate risks to Murray-Darling Basin Plan outcomes. *Australasian Journal of Water Resources*, 1–21. <https://doi.org/10.1080/13241583.2026.2639540>

### 3.3 Comments on “Review of the WATHNET model and yield modelling approach” report

1. Need to make stronger recommendations to transition to transient/dynamic WATHNET modelling instead of steady state modelling. There are many reasons for this (as per what HARC includes in their report and as per what George Kuczera said at the workshop on 21 April 2026. In addition, from a climate change impact assessment perspective, continuing with a steady state yield modelling approach is not justified because Australia’s hydroclimate is not in a steady state (and never will be).
2. It is understood that some time and effort is required to switch to dynamic WATHNET modelling but apart from being the more defensible thing to do there are also other advantages including that it reduces the uncertainties associated with selection of baseline reference period and future time slices that are required for the commonly used “delta change” methods of assessing climate change impacts.
3. Executive Summary: The key recommendations for me from this report are #69 and #70 but they are buried. Suggest adding Recommendation #69 and #70 to this table in the Exec Summary as high priority recommendations.....but update them as follows:
  - a. #69 ...suggest delete this and all associated text that argues to “retain steady state modelling”
  - b. #70 change to something like “urgently do whatever is required to transition to a dynamic modelling approach irrespective of whether operating licence conditions and design criteria change
4. Table 4-4, 2<sup>nd</sup> row “can be run with existing stochastic data”.....Why are there crosses for the two transient state columns? Both of these can be done if a temp-coverate stochastic approach is used. Stochastic data for this exists<sup>3</sup> (and can easily be updated to fit whatever purpose).
5. Page 39, 1<sup>st</sup> para. This seems inconsistent with the info that appears in the first row of Table 4-4. Here you say the required stochastic data does exist (which it does) but has not yet been widely used but in Table 4-4 the crosses in the top row suggest the required stochastic data does not exist (which, as per my previous comment, is not true – there are at least two existing sources of stochastic data that could be used: (i) the NSW DCCEEW palaeo-stochastic datasets and (ii) the Kiem et al. (2021) data<sup>3</sup>).
6. Page 39, last para: Suggest delete or revise this para. As per previous comments, the transition to a dynamic modelling approach should happen urgently irrespective of what happens with operating licence requirements.
7. Page 41, last two recommendations. Delete/revise as per previous comments.

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<sup>3</sup> Kiem, A. S., Kuczera, G., Kozarovski, P., Zhang, L., & Willgoose, G. (2021). Stochastic generation of future hydroclimate using temperature as a climate change covariate. *Water Resources Research*, 57, 2020WR027331. <https://doi.org/10.1029/2020WR027331>



**Subject:** Feedback on WATHNET Model Independent Review 2026  
**Date:** 28 April 2026  
**To:** Stephanie Kermode, Project Manager WATHNET Model Independent Review 2026, HARC  
**From:** Brendan Berghout, Senior Water Resources Engineer, Hunter Water

## Background

Thank you for the invitation to participate in the 2026 review of the Sydney system WATHNET model.

As with WaterNSW, Hunter Water uses numerical simulation of its headworks water supply system to inform critical decision making for capital works planning, yield analysis, optimisation of operating rules and planning for drought. In addition to being able to assist with the review process from this perspective, the information supplied and the Review Workshop have exposed us to developments in state-of-the-art hydrological techniques that will assist our processes in the future, meaning that the interaction has helped Hunter Water as well as hopefully helping WaterNSW.

Hunter Water’s review is limited to commenting on the methods and concepts described in the documents provided by HARC and as discussed at the Review Workshop. We have not attempted to look in detail at the WATHNET and other models used by WaterNSW and assume that this investigation has been completed by HARC. Our review comments are generally ‘by exception’, with no commentary provided in areas that we haven’t explored in detail or are outside of our experience.

The documents that we received and the level of review provided are provided in the following table:

Document	Level of review
<b>Sydney Water feedback on WaterNSW Supply System Model Review</b>	Viewed but not reviewed
<b>Statement of Work – WATHNET Model Independent Review 2026</b>	Viewed but not reviewed
<b>WATHNET Review Delivery Methodology</b>	Viewed but not reviewed
<b>Review of Climate Change Impact Assessment April 2026</b>	Reviewed by Natalie Lockart and we have no comments
<b>Review of the WATHNET model and yield modelling approach April 2026</b>	Reviewed – comments by Brendan Berghout
<b>Review of historical and stochastically generated hydrology data</b>	Reviewed– comments by Brendan Berghout

## Review of the WATHNET model and yield modelling approach April 2026

- Table E1 – List of high-priority recommendations
  - This list generally seems reasonable, though I question Item 55 being in the ‘high’ impact list. Consideration of LTAAELs outside of the WATHNET model environment may be appropriate if they are not constraining for the existing system and are likely not relevant when considering augmentation options (because augmentation of a rain or streamflow dependant source will often require a corresponding review of the rules for the scheme to be effective). I tend to agree with the discussion that inclusion of LTAAELs to flag violations for further investigation rather than as hard limits, may be useful.
- Section 4.3 – Uncertainty
  - We agree that uncertainty in the yield figure should be demonstrated and the approach that has been proposed seems reasonable. Alternatively, WaterNSW could investigate stability in the yield estimates relative to the number of replicates analysed. Replicate thinning could be investigated to reduce run times for analyses using larger replicate sets.
- Section 4.4.2 – Dynamic or transient state modelling
  - It is recommended that this section be split and a new section created to separate out the discussion of the pros and cons of each modelling approach from the description of the dynamic approach.
  - I agree with the pros and cons as presented. I generally find that transient modelling ticks more boxes conceptually, but it is hard to implement in a meaningful way. It reflects the reality that risk at any point in time is a function of starting storage, changing demand and changing climate, which is a reality that can be problematic for long lead-time water resource augmentation projects. The required timing of these projects may vary wildly as a function of starting storage (if using the dynamic approach), and this can become difficult to manage with stakeholders including Treasury. A cycle of now we need it, now we don’t, can be damaging, possibly terminal, to a project’s chance of success.
- Demand model
  - At the Review Workshop, we were surprised by the description of how demand is modelled within WATHNET for the Sydney system. We prefer to use a Beatty-style demand model that is run using scripts within WATHNET. Specifically, our demand model parameters are fitted to make use of information that is available within our WATHNET model (i.e. rainfall and ET), and includes a soil-moisture model. Temperature isn’t available so instead we fitted (and run) the model using table of average maximum temperature for each month of the year. This cut-down version of a full climate-based demand model works well enough for our purposes.

## Review of historical and stochastically generated hydrology data

- Section 4.1.3.1 – Regression relationships
  - We are a bit puzzled by this approach. Is there a good reason to use regression relationships instead of rainfall runoff models for the purpose of extending streamflow datasets?
- Section 5.2.3.1 CMCR
  - With regards the discussion regarding CMCR, why not express inflow in mm, with catchment area dynamically altered as lake area changes? I feel this should work pre and post dam? If the relative change in catchment area is small, then the impact of exposed lakebed inflow is probably a second order issue, ok to ignore.
- Section 5.2.3.2 Sacramento model
  - We agree with the strong recommendation that the rainfall-runoff models need to be calibrated using methods suited to yield estimation (i.e. preservation of runoff volume at a similar timestep as used in the synthetic climate generation method). It is noted that not all modelling packages offer suitable objective functions for this purpose.
- Section 5.2.3.3 WATHNET nodal inputs – treatment of negative inflows
  - Based on our experience we suggest exploration of possible causes of negative inflows before deciding how to deal with them.
  - Possible issues to explore include bias in estimated spill or release volume (e.g. consistent instrument error), bias in the evaporation estimate or bias in a pumped input.

- It may be useful to fit a rainfall runoff model to assist with identifying outliers in the CMCR estimate of inflow that may occur at times that don't show up in months where the estimated inflow is negative.
- Specific attention needs to be given to strings of months with negative estimated inflow as this can be indicative of a systematic problem during droughts. Systematic under-estimation of storage losses during droughts would lead to over-estimation of yield.
- Section 5.3.5 Method of fragments (k nearest neighbours)
  - The importance of being careful to select an appropriate k is a function of how important it is to simulate 'intra-season' storage performance. In our case, with a 12-month 'season' used when generating synthetic climate, and critical droughts lasting only 2 to 3 years, simulation of intra-season storage behaviour is very important, but this may be less of an issue for Sydney where critical droughts are longer. Hunter Water uses  $k = 1$  because many years ago, likely using a predecessor of the MSSSCAR synthetic climate method, we found that selecting a larger k reduced our ability to replicate the frequency of 18-month storage draw-downs, something that concerned us. Following the Review Workshop discussion we intend to experiment with different k options and also different season lengths.



## MEMORANDUM

<b>To</b>	Stephanie Kermode, HARC
<b>Cc</b>	2026 Expert Panel Members
<b>From</b>	Tim Purves, Icon Water
<b>Date</b>	28/04/2026
<b>Topic</b>	<b>Sydney WATHNET Model Review</b>

### Introduction

The following points represent my notes on HARC's review of the WaterNSW Sydney WATHNET model. The final section addresses HARC recommendations that could be modified or added, in my opinion. The vast majority of HARC's recommendations are not addressed here, indicating either that I tacitly support the recommendation or that I defer to the expertise of the HARC authors in this space.

### Rainfall-Runoff Modelling

- A consistent approach to rainfall runoff modelling should be used for all purposes. A common model, parameters and input data (i.e. SILO, AWAP, single site or multi-site) should be adopted for climate change analysis and historical period extension.
- Models should be used to extend historical series, rather than regressions, unless regressions can be shown to perform as well as models.
- The performance of rainfall-runoff models in the Tinderbox Drought is similar to Icon Water's daily timestep models calibrated before the drought for Canberra's water supply catchments. Generally good model performance is not indicative of good model performance in extreme events. Ensuring satisfactory model performance in extreme events is necessary for water security planning given the significance of these events in accurately determining yield. This need is further reinforced by the incorporation of climate change.
- Model behaviour indicates that historical runoff generated using these models may also be overestimated if the historical period contains extreme drought events similar to the Tinderbox Drought. Improving the rainfall-runoff models could therefore improve the accuracy of the yield calculation by adjusting the historical data sequence.
- In the Canberra region (and likely elsewhere), the Tinderbox Drought was characterised by successive years of progressively lower rainfall, culminating in the very dry 2019 conditions. 2019 runoff was lower than previous years with similar rainfall; however, this does not necessarily represent a change in catchment behaviour. Instead, this may indicate that antecedent catchment conditions play a significant role in runoff. We know that this is the case (Canberra & Sydney) through testing the lag inflow relationship and applying antecedent conditions in the WATHNET model.
- It is therefore important that any rainfall-runoff model adopted can reproduce the influence of multi-year rainfall deficits on runoff by adequately incorporating the changing catchment conditions.
- Icon Water significantly improved model performance through adopting:

- monthly timestep rainfall-runoff models (WAPABA, with abcf also tested and providing similar performance).
- Calibration objective functions that incorporate total flow bias, flow bias during drought conditions (Millennium and Tinderbox) and transformed NSE using  $Q^{0.2}$  or  $Q^{0.5}$ . Transforming the flow avoids biasing the model fit to high flow periods, but conventional NSE can still be calculated as an additional measure. Flow duration curve accuracy could also be incorporated into the objective if desired.
- Even if using daily timestep models, Sacramento is unlikely to be my first choice.
- I recommend tempering the recommendation to use only at site rainfall. There are two arguments for avoiding gridded rainfall:
  - At site rainfall (from one site or multiple sites) will provide a better calibration than gridded rainfall products
  - At site rainfall provides a better and more transparent means of infilling and extending data

In my view, the first of these arguments should be tested through calibrating models to different input data sources and examining appropriate calibration and validation metrics, rather than taken as fact.

The use of gridded rainfall effectively outsources the infilling and extension process to an external agency. In my view, this can potentially result in better outcomes than relying upon simple correlation methods to infill and extend data, especially in the case of AWAP data. Gridded rainfall products can and should be tested against appropriate high quality historical records and examined for non-climatic trends.

Recommend that gridded rain data is appropriate for use when:

- It provides calibration performance as good or better than when using at-site records; and
- It can be demonstrated that it does not contain strong non-climatic trends when compared against at-site data.
- Recommend that WaterNSW:
  - Adopt a rainfall-runoff model calibration technique that combines drought performance with overall performance.
  - Using the metrics developed above, consider various models including monthly timestep models. For example, WAPABA, abcf, Sacramento, GR4J & SMAR-G could be trialled. Adopt the best performing model.
  - Using metrics developed above, consider the use of single site, multi site or gridded rainfall. Adopt the best performing rainfall source. Approach need not be consistent across catchments.
- Monthly timestep models have the additional benefit of reduced computational complexity. This opens up options that may be difficult with daily timestep models. For example, a dynamic inflow sequence incorporating climate change could be generated by:
  - Generating stochastic climate (rainfall, evaporation, temperature) for a baseline period
  - Scaling the climate variables to account for an increasingly changing climate
  - Converting this to runoff using monthly rainfall-runoff model

I am not necessarily recommending that this should occur, merely providing an example of the potential benefits of reduced complexity.

## Historical Data

- Suggest testing final adopted historical data inflow sequence for discontinuities using the rainfall-runoff model output (e.g. double mass-curve of historical inflows v rainfall-runoff output). This may highlight changes in either series that warrant further examination. Possible drivers of change in the historical data sequence include:
  - Landuse

- Bushfire
- Data inaccuracy (runoff or climate variables)
- Change of calculation method
- Climate induced catchment response
- If the rainfall-runoff model is sufficiently accurate, it can be relied upon as the source of inflow behaviour rather than the historical record. For example, inflows can be generated using climate change adjusted rainfall, using a rainfall-runoff model calibrated to reproduce current catchment behaviour. Taking this approach avoids introducing errors from the factors listed above, but risks introducing errors within the rainfall-runoff model. Rainfall-runoff performance would need to improve significantly to consider this approach.

## Dynamic v Stationary Simulation

- Traditional yield analysis with a stationary climate and demand remains a suitable method for calculating system yield.
- However, there are benefits to simulating with a dynamic demand and (possibly) climate, such as:
  - Can incorporate initial conditions (storage and antecedent catchment inflow conditions) into the run – this may improve security somewhat at high initial storage, as well as providing a more realistic projection.
  - Can better simulate the impact of system augmentation by applying augmentations within the run. Augmentations could be triggered at a given date, a given demand threshold or when going below a storage threshold.
  - Can simulate supply and demand drought management responses to low storage events – these can be turned on in each replicate only if the storage threshold is met. This can determine the likelihood of a drought management plan not working due to worse than anticipated climate.
- As per HARC's report, level of service must then be calculated looking at all the replicates for a fixed time period (e.g. a given year), not by examining the entire run. This is problematic for the very low storage yield metric unless a very large sample of replicates is generated. However, this metric possibly requires review to align with industry best practice approaches. Given the consequence of Sydney running out of water, this is unlikely to be acceptable even at very low likelihood. A metric that examines the feasibility of implementing demand and supply measures in time to avert running out of water may be more suitable. This metric could be assessed using the stochastic data and/or other extremely low inflow sequences. Alternatively, the model could be run in stationary mode to address the current metric.
- Adopting dynamic simulation may help to address some of the stakeholder feedback received from Treasury, for example:
  - *the question of 'should we invest now' for augmentation is just as important as long term planning based on portfolios of potential investments*
  - *It's our understanding that WATHNET cannot directly estimate the risk of failure at any point in time, or the cumulative risk of failure year by year.*
  - *What role does current storage level play in the analysis of Yield, and why? If not, how should current storage levels be used to assess water security risk?*
- Disagree with HARC's comment that dynamic simulation "provides no information on the gap between supply and demand over time". Dynamic simulation can be used to determine yield and produce the same example supply demand curves generated using stationary simulation. Yield can be defined as the demand occurring in the year when one or more of the level of service metrics is no longer met.

## The WATHNET Model

- HARC is best placed to conduct and document the detailed model review.
- My preference is to include dead storage in all dams and constrain the outlet/supply nodes to not use the dead storage. Scripts can calculate active storage within the model as required.
- Savings are identical for level 3, level 4 and level 5 water restrictions. Suspect that in reality, larger savings are possible. Incorporating these savings into the model, along with drought management actions, would more realistically simulate low storage events.
- Agree with HARC comments regarding applying restrictions to restrictable component of demand.

## Climate Change

- Agree with HARC's recommendations. Agree pattern scaling provides the best approach and support applying this to NARClIM 2.0. Pattern scaling suits a dynamic modelling approach, but is equally applicable to a stationary climate. I support adopting pattern scaling over alternative approaches such as time-slice or temperature covariate analysis.

## Comments on HARC Recommendations

Part 1, #8 & Part 3 #2: Recommend that gridded rainfall is appropriate for use in some applications when the two conditions discussed above are met.

Part 1, #22, #23, #25: Recommend that alternative rainfall-runoff model approaches be considered in addition to Sacramento. Recommend that monthly timestep rainfall-runoff models be amongst the options considered.

Part 1, #36: In addition to system yield, other metrics of relevance can be tested. For example, lowest system inflows recorded within a period of n years.

Part 2: Recommend explicitly specifying that the model should incorporate both dead and active storage. Active storage may then be calculated and applied within the model.

Part 2: Recommend considering applying larger demand reductions at low storages. Current demand reductions likely do not represent the savings that could be achieved in response to a very low storage event.

Part 2 "Consider a dynamic modelling approach if operating licence conditions and design criteria change": Recommend that a dynamic modelling approach be considered even without change to operating conditions and design criteria. If necessary, the model can be maintained in a state where it can be run in either stationary or dynamic mode. At least two of the three design criteria can be evaluated in both modes. The dynamic modelling approach can be used to examine stakeholder queries regarding the impact of initial storage, as well as communicate the probabilistic impacts of different augmentation strategies.

Part 3: Recommend explicitly stating that the baseline yield assessment should incorporate climate change when simulating current climate. Climate change has already occurred and is influencing weather patterns. This is readily apparent in the rise in global mean temperature, for example. A narrative that climate change will occur in the future but need not be incorporated into current modelling estimates no longer withstands scrutiny.

# OFFICIAL

WaterNSW WATHNET Model Independent Review 2026

Independent Review Panel Member Feedback

Kim Seong (KS) Tan, 13<sup>th</sup> May 2026

## Preamble

Thank you for the invitation to participate as an expert panel member in WaterNSW WATHNET Model Independent Review 2026 undertaken by HARC.

This short report summarises my feedback after reviewing the relevant documents provided by HARC, and following discussion in the panel workshop convened by HARC on 21 April 2026.

This panel participation has been approved by Melbourne Water in my capacity as a Melbourne Water employee, providing time through in-kind contribution collaborating and sharing experience between Melbourne Water and WaterNSW, noting that any feedback could be personal professional opinions and judgement of the panel member and may not represent position of Melbourne Water.

The following documents provided by HARC was received on 14 and 15 April 2026:

- HARC Hydrology Data review memo, and written stakeholder feedback items (from Treasury and Sydney Water)
- HARC WATHNET Model review memo
- HARC climate change impacts memo
- WaterNSW hydrology memo

It is noted that the three memos prepared by HARC as part of this review (HARC Hydrology Data review memo, HARC WATHNET Model review memo, and HARC climate change impacts memo) collectively presented about 130 recommendations.

In general, the reviewer noted that HARC has undertaken a reasonably comprehensive understanding and assessment of the above three aspects. the majority of HARC's recommendations are found to be acceptable and therefore supported.

In undertaking this short assignment, it is not possible for the reviewer to review every aspects and details of the hydrological data preparation and analyses, WATHNET setup and modelling, climate change projections and applications by WaterNSW with respect to the Greater Sydney water resources system and supply security. The feedback provided are therefore focusing on those specific aspects that are thought to be important from our shared experience in Melbourne and/or aspects that are ambiguous or contestable which would likely be benefiting from further clarifications or investigations.

1. Review of historical and stochastically generated hydrology data
  - 1.1. Historical rainfall data inputs - use of gauged and gridded data and data quality checks
    - 1.1.1. HARC Recommendation #8: Use gauged rainfall for deriving streamflow in all applications unless gridded rainfall is the only available source of data. Agreed in principle – however, if only single rain gauge available or if gauges do not cover upper catchment i.e. limited to measurement at lower catchment e.g. near the dam wall this will not be representative for the whole catchment and likely underestimate actual catchment average rainfall that generates the streamflow (e.g. as in Figure 1 Rainfall used to calculate current CMCR for Warragamba). Catchment average rainfall derived from Gridded products can capture rainfall spatial variability and orographic effects, but acknowledging The potential risk of bias or error in gridded climate products referred to in HARC’s report (e.g. Kuczera, 2025), this raises a broader question on the need for the Australian hydroclimate community to re-consider possible synergy and improvement to the two existing gridded products (AWAP and SILO).
    - 1.1.2. #9: Identification of non-climatic trends or step changes: for each rainfall time series used ...for the period 1909-2025...against...the nearest Bureau of Meteorology climate change reference site. Suggest to exercise caution when de-trending climate data unless it is supported by non-climatic factors (e.g. changes in instrumentation or site exposure). This is to avoid removing real climate trend (e.g. catchment average rainfall derived from gridded products that could be real and should be preserved (e.g. due to orographic effect during wetter decades 1950-60s with unusually high rainfall in the upper catchments/Alpine region), where such extreme high rainfall may not be present in gauged rainfall at lower elevation even if it is a high quality reference network site.
  - 1.2. Historical evaporation data inputs - data quality checks, estimation of lake evaporation
    - 1.2.1. Suggest to consider the option of estimating reservoir evaporation using Complementary relationship method (Zhang et al XXXX). Based on recommendation in a study undertaken by CSIRO in 2000, Melbourne Water has developed a framework for implementing an operational data store for estimating reservoir evaporation (Tan et al 2024). The framework is currently still being tested before it can be operationalised.
    - 1.2.2. Figure 2 caption - Correction/typo “Potential evaporation used to calculate current CMCR for Warragamba showing a) time series of

monthly...rainfall (should be evaporation)... and b) cumulative annual rainfall (again should be evaporation)".

1.3. Historical inflow data: approaches for CMCR, Sacramento calibration and results, consistency of WATHNET nodal inputs

1.3.1. Support HARC recommendation #16: Develop and maintain documentation on the rationale for retaining legacy streamflow input datasets for the 1909 to approximately mid-late 2000s period, and the periods of inflow data subject to review or update. In particular, include a clearer explanation in the documentation of why inflows for the 1960–2007 period from previous model updates have been preserved, when it appears that the revised CMCR analysis could be used to regenerate the monthly inflows for this period.

- Why is the "likely impact on yield assessment" ranked as "Low\*", why not "Medium"?

1.3.2. Support HARC recommendation #18: Replace water balance values and regression-based values prior to the 1960s with CMCR estimates. If CMCR estimates cannot be applied for these locations and time periods, replace with results from rainfall-runoff models that are suitable for yield estimation.

- The "likely impact on yield assessment" should be Medium (not low).

1.3.3. Figure 3 caption - Correction/typo "Potential evaporation used to calculate (delete) current CMCR for Warragamba showing a time series of monthly...rainfall (should be inflow)... and b) cumulative annual rainfall (again should be inflow)".

1.4. Stochastic data approach: validation approach, input data for calibration, parameters (seasonality, value of k, longer memory models), paleoclimate data, application in WATHNET for assessing system yield

1.4.1. HARC recommendation #32: Generate synthetic data using  $k = 5$  and  $k = 10$  and investigate the prevalence of monthly temporal patterns for near-average or "wet" years being applied to synthetic low flow year.

1.4.1.1. Noted HARC report highlighted that "As more inputs are generated in WATHNET there is an increased chance of temporal patterns being applied to years which are not climatically or hydrologically similar".

1.4.1.2. A possible simplified alternative method is to allow WATHNET to assign a primary variable and disaggregate the generated annual values of all variables into monthly scale using the method of fragments, with a set of monthly temporal patterns from a historical year sampled from The nearest  $k$  years determined based only on the generated annual values of that primary variable. cross-correlations of

monthly temporal patterns with all the other variables in the stochastic data generation are therefore “automatically preserved”. For example, a concurrent set of monthly temporal patterns from historical years can be sampled based on the nearest k historical years with respect to the generated annual inflow for Warragamba dam. The other variables will then be scaled correspondingly just to match the generated annual values. This alternative may not be as elegant as the kNN algorithm using the Mahalanobis approach that focuses on statistical distance in multivariate distributions. However, it will lead to realistic concurrent monthly sequences in hydro-climatological processes that are more important to be preserve in this case.

## 1.5. Rainfall runoff modelling

1.5.1. Regarding HARC Recommendation #22: Re-calibrate Sacramento to ensure suitability for yield estimation, including incorporation of more recently collected streamflow data; and recommendation #25: Seek to improve rainfall-runoff model calibration accuracy by exploring the use of at-site rainfall inputs, alternative model calibration strategies, or alternative model structures, with the aim to use the time series outputs from these models directly in water resources modelling if suitable calibration accuracy can be achieved.

- The reviewer support the need to consider alternative model calibration strategies or alternative model structures that can better handle observed shift in rainfall-runoff relationship, such as that experienced in many Victorian catchments before, during and after the Millennium drought from 1997-2009 as highlighted in the Guidelines for assessing climate change impact on water availability in Victoria (DEECA, 2025).
- The reviewer suggests one potential approach is to explore a new framework where a rainfall-runoff model can be run in a dynamically-coupled mode with a statistical package hydroState which was recently developed to detect shift in catchment rainfall–runoff relationship between different states over time using hidden Markov method of runoff with rainfall as a predictor (Peterson et al., 2021).

## 1.6. HARC Report, Section 5.4 Summary of Recommendations

1.6.1. The reviewer suggests to move the following to High priority- HARC recommendation #31: Explore the impact of using multiple seasons on the statistical attributes of the synthetic data.

## 2. Review of Climate Change Impact Assessment

2.1. Historical climate change, hydroclimate data stationarity - any adjustment for non-stationarity in inflows due to non-climatic factors such as historical bushfires

2.1.1. There is no mention about treatment of hydrologic non-stationarity due to the impacts of historical (or potential risks of future) bushfires on short and longer term catchment streamflow yield in the report? The Reviewer raised this during the panel workshop 21<sup>st</sup> May 2026, noted there was discussion and clarification that such impact is considered insignificant for Greater Sydney water supply catchments which are dominated by mixed Eucalypt forest (and not Mountain Ash forests such as in the case of the Greater Melbourne water supply catchments). For clarity, it is suggested that a small section be added to provide a summary of the background, discussion and conclusion along with the relevant references on this issue.

2.1.2. HARC Report Section 4.1 Summary of previous climate change review outcomes – with reference to previous review recommendation : “The use of annual temperature as a covariate is an example of a defensible approach to assessing climate change impacts on system yield”. HARC identification of WaterNSW response was that : “This has been tested for Sydney’s water supply catchments. HARC’s view is that this approach is well suited to addressing non-stationarity in historical observations due to global warming, but it is less preferred for climate change projections compared to other available techniques (e.g. pattern scaling – see Section 6.10.2 of this review)”.

- o The view of the reviewer differs from HARC’s in that the temperature covariate approach is actually well suited to addressing non-stationarity in both historical observations as well as future climate change projections associated with global warming. Using temperature as the identified covariate, temperature adjusted multi-site inflows can be generated. Statistics of this stochastically-generated non-stationary series can then be compared with the instrumental record, a fixed-period reference (e.g. post 1975 step change adjusted series ), and a progressive climate change series (e.g. based on pattern scaling approach), to illustrate differences and variability in inflows and water availability. The results can be used to demonstrate how stochastic -covariate method can complement, or provide an alternative to, fixed-reference period adjustments when assessing non stationary inflows, in the current climate and under near-future climate change conditions.

2.2. Climate change scaling factors including climate reference period for the scaling and parameters being scaled

- 2.2.1. Agreed with HARC's overall findings and recommendations, in particular HARC recommendation #17: "Climate change scaling factors: Support local testing of the pattern scaling approach by the Metropolitan Climate Change Working Group and, together with other stakeholders, transition to its use for climate change projections, if it is found to be more fit-for-purpose locally than the time slice method in reducing the signal-to-noise ratio from the climate change projections".
- o The reviewer supports this HARC recommendation and can confirm that this is consistent with the latest updated climate change projections to be adopted in Victoria. the pattern scaling approach has now replaced the time slice method in the latest Victorian Guidelines for assessing climate change impacts on water availability (DEECA, 2025).
- 2.2.2. Noted typo in Table 5 Comparison of reference periods in different applications, row 1 the 40 years historical reference period should be 1980 to 2019 (not 2009).
- 2.3. Climate projection data source, climate model selection, emission pathway selection
- 2.3.1. Agreed with HARC's overall findings and recommendations. Noted HARC recommendation #9: Emission pathway selection: Retain the current practice of preparing climate change factors for all NARClIM2.0 emission pathways, so that they are available to use in sensitivity analyses". And that Table 3 Summary of key assumptions and methods for WaterNSW climate change impact assessment, indicating that in the 2026 approach: "SSP2-4.5, SSP3-7.0, with SSP1-2.6 as a lower priority (because Sydney Water doesn't currently use it) if time and resources permit"
- o The reviewer supports that both emission pathways SSP2-4.5 and SSP3-7.0 be adopted . This is consistent with the updated DEECA 2025 Guidelines for Victoria.
- 2.3.2. Noted HARC recommendation #20: "Climate change impact on demands: WaterNSW request that Sydney Water provide consolidated documentation to WaterNSW about its demand modelling methods and assumptions under projected climate change and any associated quality control checks on the calculated climate change scaling factors".
- suggest to consider using the CLINX approach currently applied in Melbourne's water resources planning model. As described in the 2005 Melbourne Water Climate Change Study (Jones et al, 2005), the climate adjustment (CLINX) factors are derived for each month in the historical dataset used to represent future scenarios, using a regression relationship with climate data. The independent variables of the regression relationship are: number of raindays, total rainfall and average maximum temperature for

each month. However, because data for estimating changes in raindays were unavailable in climate change projections, number of raindays could be replaced with monthly potential evaporation values. The procedure for modelling climate-driven water demand is

1. Estimate the monthly demand under average climatic conditions based on annual demand under average climatic conditions (disaggregation from annual to monthly)
  2. Estimate the climate-sensitive and climate-insensitive components of monthly demands
  3. Estimate the climatically-adjusted monthly demands by adjusting the climate sensitive component using a CLINX factor above.
- 2.4. Low likelihood, high impact climate change scenarios

2.4.1. Noted Section 6.12: Highlighting that “Devising plausible and meaningful low likelihood, high impact climate change scenarios that do not come directly from climate model projections can be challenging. One option that has been recommended in the DCCEE draft metropolitan climate change technical guidance is to undertake supply system shock testing that assesses the impact of a loss of critical water harvesting sources or distribution assets for an extended period (DCCEE (NSW), 2026b). This would be an indicator of potential risks under low likelihood, high impact climate change scenarios that may fall outside of the impacts projected by NARCIIM2.0. Such an approach allows system resilience to be assessed in the event of natural hazards whose likelihood may be increased under future climate conditions. System shocks would need to be derived collaboratively by supply system operators and planners but could include an extended outage of the Sydney Desalination Plant, or disruption to the supply from particular storages”.

- o The reviewer can also relate experience during extended dry conditions whereby particular demand zones that rely on specific sources of supply could potentially be subjected to localised water shortages more severe than the broader system due to unusual spatial variability in water availability and/or limitation in existing transfer network.
- o Such low likelihood, high impact scenarios including catchment bushfires that may not be directly informed by climate change model projections can be challenging, and should be investigated

### 3. WATHNET Model Independent Review

#### 3.1. General overview

- 3.1.1. Noted two stakeholders (Sydney Water and NSW Treasury) provided memos with additional comments as part of this WaterNSW WATHNET Model Review process, which was captured in HARC report Section 2.2.2.
  - 3.1.2. For example, The Sydney Water memo emphasised the need for the report to recognise and discuss the limitations of yield modelling; asked that a description of the model's dependency on past inflow patterns and probabilities be provided; and to note that its purpose is not to predict the timing, severity and/or duration of drought conditions. It also requested confirmation that yield modelling will capture amongst others, full time flexible operation of Sydney Desalination Plant, and Water Sharing Plan rules. lower likelihood events, and that water availability can also be affected by raw water quality
  - 3.1.3. The NSW Treasury memo discussed the need to take decision makers on a journey, and to better explain model application for different purposes. For example, a desire for improved transparency of modelling assumptions and methods, linkage between long-term yield analysis and the potential for modelling to inform near to medium term augmentation decision planning such as using dynamic yield approach.
  - 3.1.4. The reviewer can reflect that These comments are highly relevant practically and raised some important system planning and operational issues that we can share experience in large complex urban water supply system, and therefore warrant further investigations. Most of these were included in HARC report Appendix A, minutes of 24<sup>th</sup> February 2026 Project Briefing and Stakeholder Feedback Workshop as part of this WATHNET Model Independent Review 2026 (in which Melbourne Water (Tim Hatt, Udaya Kularathna , KS Tan) were invited to share experience and provide an overview on water resource strategy development, yield modelling and drought planning approach for Greater Melbourne, as a utility with similar regulatory obligations to WaterNSW). The reviewer would like to highlight the following key areas that are considered important and relevant (which have also been raised in the Sydney Water and NSW Treasury feedback mentioned above and captured in HARC's WATHNET Review Report), and therefore should be considered for further investigations as part of the current or future WaterNSW WATHNET model review.
- 3.2. Water security - level of service (LOS), drought contingency reserve volumes (DCRV) versus minimum operating level (MOL)
    - 3.2.1. Water security – HARC report Section 2.2.2 Stakeholder memos indicated: *" The Sydney Water memo emphasised the need for the report to clearly articulate the broader purpose of the supply system model in assessing, monitoring and informing decisions to manage Greater Sydney's water security, and recognise and discuss the limitations of yield*

*modelling," and that yield modelling should include consideration of, amongst others, "lower likelihood events, and that water availability can also be affected by raw water quality".*

- 3.2.2. LOS - Noted HARC report Section 4.2 Assessment of outputs against design criteria indicated: *"The Sydney water supply system is required to meet three Level of Service (LoS) design criteria which aim to limit the frequency and severity of restrictions and ensure a very low likelihood that the system will run out of water...current level of service design criteria are: Security - storages do not approach emptiness (defined as 5% of water in the storage) more often than 0.001% of the time, or one chance in 100,000 in any one month; Robustness - imposed water restrictions should not occur more often than once in every ten years on average; Reliability - imposed water restrictions should not last longer than 5% of the time on average, or 5 months in 100 months".*
- 3.2.3. DCRV - Noted HARC report Section 3.5.3 Restriction rules indicated: *"It is noted that no reserve volume has been specified. As discussed in WSAA (2024) use of a reserve volume is a drought contingency measure that can be linked to lead time required for emergency response. Its use and size are a function of risk appetite and the desire to guard against climate uncertainty. It is recommended that use of a reserve storage be explored and the rationale for its adoption or otherwise documented".*
- 3.2.4. MOL - The reviewer would like to suggest that a more practically realistic total system minimum operating level (MOL) be further investigated to help define the LOS for water security. This is because it may be too risky and therefore unacceptable for a large city like Greater Sydney to run out of water i.e. storages approaching emptiness defined as low as 5% of water in the storage, even though under a very low likelihood scenario at *one chance in 100,000 in any one month*. For example, this can be based on a detailed study by assessing aspects of the hydraulics and water quality characteristics for each of the reservoirs within the Greater Sydney water supply system. Similar detailed study of the MOLs for all the ten harvesting and transfer reservoirs for the Greater Melbourne's water supply system was undertaken recently in 2020. The analysis included reservoir elevation schematics and tables to define various intake and operating levels subject to different hydraulics and water quality constraints at low storage levels including the dead storage. A total system 'normal' MOL (enabling water to be supplied to Melbourne's retail water companies that satisfies contractual pressure and quality requirements) of 25% storage level is currently adopted for drought preparedness planning to derive the Water Outlook zones for Melbourne and this MOL also forms one of the key assumptions for yield assessment (for context, storages have not been

operated below this level, as storage volumes fell to a historic low of 25.6% of capacity in June 2009 during the 1997-2009 Millennium Drought). Such a MOL study can also be extended to help estimate the feasibility, lead time and cost of any potential contingency measures to access water below the MOL, as well as any potential localised supply constraints due to individual reservoir's characteristics, demand zones and/or transfer network constraints, and recognising that compounded events such as catchment bushfires can lead to water shortages threatening water security especially during drought and dry conditions. In summary, if not already, without detailed study to understand and re-define the operational risk of individual reservoir and total system minimum operating levels, use of the current 5% storage level as LOS for determining water security for Greater Sydney may potentially present a false sense of security.

### 3.3. Drought preparedness and response planning approach

3.3.1. Restriction trigger levels in relation to drought response planning approach - Noted HARC report Section 4 Review of yield modelling approach, Table 4.1: Yield model assumptions proposed by WaterNSW...indicated: "*L1 Storage Trigger 60% Aligned with Greater Sydney Drought Response Plan (GSDRP); L2 Storage Trigger 45% (Aligned with GSDRP); L3 Storage Trigger 35% (Aligned with GSDRP)*", and Table 3.7: Restriction regime option 1 listing 5 Restriction Levels as : 0.60, 0.45, 0.35, 0.25 and 0.15 .

– The reviewer would like to emphasise that DRP is a critical component in water security planning. It would be helpful to provide the details on how these restrictions triggers based on storage levels at 60%, 45%, 35% (and 25%, 15%?) corresponding to L1, L2, L3 (and L4, L5?) respectively, are derived in the GSDRP. For example, what are the reference baseline datasets, modelling assumptions, water security criteria e.g. design drought risks (annual exceedance probabilities AEP), water security duration or lead time, etc.

3.3.2. Sharing experience in drought planning approach –opportunity exists for WaterNSW to share experience from other large urban water system, for example currently Melbourne's Drought Preparedness Plan (see GWW, SEW and YVW, 2022) adopts a set of annual water outlook zones (with corresponding drought response actions including possible restriction triggers in each zones) based on total system storage TSS on 30<sup>th</sup> November. Key elements of this DPP approach (see HWRs 2024 paper: Tan et al 2024 "Adaptive Water Outlook Zones – A Stochastic Drought Risk Approach") include the derivation of "Action Points" or boundaries that define these zones using a stochastic method to assess drought inflow risks (e.g. 1 in 100 and 1 in 200 AEP), the increasing consumptive demand , carryover

drawdown of non-metro consumptive users, and the estimated demand savings based on actions to be taken within those zones. Using Melbourne's water resources planning model, a set of new water outlook zones were reviewed and tested by simulating the behaviour of Melbourne's water supply system for a 2 and five-year water security lead time under different combinations of potential drought risks and sequences. Continuous review and updating is necessary, with the 'Be Proactive' zone now lifted from 60% to 75% of total system storage. It is likely that a major supply augmentation will also be needed within the next 10 years to balance the increasing demand from population growth and declining streamflow under climate change.

### 3.4. Linkages of yield assessment to drought response planning approach –

#### 3.4.1. what are the linkages of the DRP zones or restriction triggers to yield assessment?

- For example, if Melbourne's total system storages (TSS) fall below the 'Normal Minimum Operating Level' of 25% then it is difficult to ensure that water supply pressure and quality requirements can be met, without undertaking extreme drought contingency measures. This 'Normal Minimum Operating Level' therefore forms the lower boundary of 'Critical Water Use Only' zone.
- The 'Critical Water Use Only' (CWUO) zone at 45% TSS has been derived so that this will allow sufficient buffer to avoid the TSS from falling below the system normal MOL. The water resource system analysis was undertaken based on an extreme drought scenario e.g. a 1 in 200 annual exceedance probability (AEP) assessed over a 2-year water security lead time. The 45% trigger for the CWUO zone will therefore trigger additional drought response actions including potential severe water restrictions to avoid storages falling below 25% under an extreme design drought scenario, while which will allow lead time for initiating drought contingencies and/or new supply augmentation.
- above the CWUO zone, The combined 'Be Proactive' and 'Act Now' zone was in turn derived (currently at 75% TSS) so that this will allow sufficient buffer to avoid the TSS from falling below the CWUO zone (at 45% TSS), based on e.g. a 1 in 100 AEP drought scenario assessed over a 5-year water security lead time. This 75% trigger for the combined 'Be Proactive' and 'Act Now' zone will therefore enable time to implement drought response actions with potential mild water restrictions to avoid storages falling below 45% TSS.
- As Melbourne's Drought Preparedness Plan (DPP) is reviewed every five years, the zone levels are expected to go up with increasing demand under population growth and reduced catchment inflow under projected climate

change.

- The zones or restrictions triggers derived in the DRP (including the corresponding demand savings, along with the MOL) therefore formed a robust and defensible basis for managing and responding to droughts, and it also underpinned and closely linked to all subsequent yield modelling for assessing water security of the system (both dynamic and static yield modelling).

3.4.2. Yield modelling process versus setting of restriction trigger levels – Also noted HARC report Section 4.1.4 Demand and restriction settings indicated: *“The process of yield modelling involves increasing demands until design criteria are just met. If for example demands in the system are 20% higher than they are currently, restriction triggers would be shifted accordingly to give the same lead time between restriction levels. On this basis, it is recommended that for yield modelling restriction triggers be shifted in line with increases in demand”*.

- This is not very clear, it would be helpful to provide further clarifications or details of the approach. For example, does this mean that in yield modelling, restriction triggers can be shifted to higher (or lower?) storage levels as demand increases to give the same lead time between restriction levels, what are the upper and lower limits, and what about the other modelling criteria?

### 3.5. Dynamic yield modelling

3.5.1. The reviewer noted and support the high priority in HARC recommendations #69: Retain the current steady state yield modelling approach, and #70: Consider a dynamic modelling approach if operating licence conditions and design criteria change. This is aligned with NSW Treasury’s Overarching comments dated 6 March 2026 indicating the desire for linkage between long-term yield analysis and the potential for modelling to inform near to medium term augmentation decision planning such as using dynamic yield approach.

3.5.2. Specifically, noted HARC report Section 4.4.2 Dynamic or transient state modelling listed the advantage of dynamic over static yield modelling in that: *“its Better represents state of a system with large storages, and provides outputs useful for a range of other purposes”, and that “Transient-state modelling of system behaviour under projected demands has the advantage that it does not pre-suppose a level of service objective. This enables changes in levels of service over time to readily be discussed, if the current level of service objective is under review. Where it has been adopted (e.g. in Melbourne), it has only been used for specific purposes (e.g. short-term storage outlooks of 1-3 years, or to support augmentation decision planning), and stationary yield analysis has been retained to*

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*enable more rapid estimates of supply system performance and to support public communication in water resource planning strategies with a planning horizon over many decades".*

1. The reviewer would like to emphasise that dynamic modelling is highly sensitive to current start storage, while this is one of the advantage in projecting system behaviour from current conditions as a probabilistic outlook with non-stationary inputs of a gradually growing demand and incremental impacts of climate change over time, modelling will need to be periodically updated (and the outputs communicated clearly) e.g. every 6 or 12 months especially for making key decisions during periods with rapidly changing extreme climate behaviour such as when the system is experiencing very dry or very wet years.