Stage 1A Victorian Constraints Measures Program

SGEFM updates, Goulburn range-finding exercise, and climate change vulnerability analysis

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1. Summary

Relaxing constraints in the Goulburn River has the potential to provide significant ecological benefits due to the current inability to manage overbank flows using environmental water. The University of Melbourne's SGEFM water resource model was used to narrow the range of potential constraint relaxation options in the mid (assessed at Molesworth) and lower (assessed at Shepparton) Goulburn River. The SGEFM was selected for this approach due to its flexibility and ability to rapidly assess multiple constraint scenarios. This was undertaken following a series of updates to the SGEFM to provide more fit-for-purpose outputs for the investigation of constraints relaxation.

The "range-finding" exercise highlighted four combinations of constraint options that are recommended for further analysis of benefits and risks. These options were assessed based on their modelled benefits in key hydrologic metrics: allocation reliability, environmental water shortfalls, and the volume of allocated environmental water shortfall that cannot be delivered due to constraints (called constrained delivery). In addition, scenarios were assessed based on the outputs of twelve ecological models that represent environmental water objectives in the lower Goulburn River. The range-finding exercise did not assess potential benefits for the mid Goulburn River.

This analysis has recommended further investigation of the following constraints relaxation targets:

Current constraint (10,000 ML/d) in mid Goulburn, 17,000 ML/d in lower Goulburn

- This was generally the lowest constraint option that still provided overall ecological benefits and avoids diminishing returns from hydrologic metrics

Current constraint (10,000 ML/d) in mid Goulburn, 21,000 ML/d in lower Goulburn

- This scenario avoids constraint relaxation in the mid Goulburn but may suffer from diminishing returns in ecological benefits.

12,000 ML/d in mid Goulburn, 21,000 ML/d in lower Goulburn

- This provided greater modelled ecological benefits just above apparent thresholds, and substantial reductions in environmental water shortfall and constrained environmental water delivery.

14,000 ML/d in mid Goulburn, 25,000 ML/d in lower Goulburn

- While the rate of benefit for relaxing constraints reduces after the previous scenario, the ecological models which rely on overbank flows improve beyond 20,000 ML/day. The best outcomes for these models is from higher flows. This scenario generally provides an 'upper bound' of possible flows which can be managed within known minor flood levels and may provide some extra benefits in the mid Goulburn which were not assessed as part of the range-finding exercise.

These four options were then further assessed for their benefits in climate change adaptation using a vulnerability-based approach. Although the relative benefits of each option differ (with higher constraint options generally delivering higher benefits in hydrologic metrics and ecological model outcomes), relaxing constraints consistently improves the robustness of the system in achieving environmental outcomes.

All constraint options deliver benefits across a relatively wide range plausible climates consistent with climate model projections. Hence, constraint relaxation is likely to offer robust climate change adaptation benefits.

However, ecological model outcomes showed that some particular constraint options delivered stronger climate adaptation benefits.

The most significant climate change adaptation benefits were seen in the highest two constraint options. This suggests that delivering overbank flows in excess of 20,000 ML/d provides important adaptation benefits, and that effective delivery of these flow thresholds is supported by moderate constraints relation in the mid Goulburn.

2. Introduction

Part of the scope of Stage 1A of the Victorian Constraints Measures Program (CMP) seeks to understand the ecological benefits of allowing the delivery of higher environmental flow components than is currently possible on the Goulburn and Murray Rivers. The University of Melbourne's (UoM) Stochastic Goulburn Environmental Flow Model (SGEFM) is being used by project partners to support the modelling of constraints relaxation scenarios in the Goulburn River. The SGEFM was previously developed to support the Australian Research Council Linkage Project LP170100598 Vulnerabilities for Environmental Water Outcomes in a Changing Climate[1]. The model differs from conventional or existing models of the Goulburn River system in that it is suited to exploratory analysis of many hundreds or thousands of scenarios due to a hybrid monthly-daily timestep that enables very fast run-times. This report outlines several stages of work undertaken with the SGEFM to support the modelling of constraints relation options in the Goulburn River, including:

- updates made to the SGEFM to better suit the needs of constraints relaxation investigations,
- a range-finding exercise to narrow potential relaxation options and determine constraints scenarios of interest in the Goulburn River, and
- climate change vulnerability analysis, and climate change adaptation benefits of selected constraints relaxation scenarios.

This analysis leverages significant work and advancements made in LP170100598. This report addresses only that work undertaken as part of Stage 1A constraints project and is intended for an internal Stage 1A team audience with a technical understanding of the project needs. It has not been written for a public audience where further explanation may be required.

Objectives for this report

- Document updates to the SGEFM to support constraints relaxation modelling
- Undertake a range-finding exercise to highlight constraints scenarios of interest that deliver ecological benefits in the Goulburn River
- Understand the climate change vulnerability of environmental and hydrological objectives within the Goulburn River, and how constraints relaxation contributes to climate change adaptation

3. Stochastic Goulburn Environmental Flow Model background

In 2018 UoM undertook a four-year research project titled Vulnerabilities for Environmental Water Outcomes in a Changing Climate. This was supported by the Department of Environment, Land, Water and Planning (DELWP), the Victorian Environmental Water Holder (VEWH) and the Bureau of Meteorology (BoM). This project sought to understand risks to environmental water objectives in northern Victorian rivers due to climate change using a bottom-up vulnerability analysis. The key difference between these analyses and more traditional scenario-driven climate change impact assessments (sometimes called top-down approaches) is that system vulnerabilities are first diagnosed based on a range of potential stressors, with the risk that climate change exposes these vulnerabilities investigated later. This has the benefit of highlighting system vulnerabilities to environmental variables that may not be projected, or projected with low confidence or high uncertainty, by global climate models. Thus, adaptation planning can still be undertaken despite lack of knowledge or uncertainty in climate projections.

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[1] LP170100598 investigators include M. Stewardson, J. A. Webb, M. Peel, L. R. Poff in addition to the authors of this report. The LP partners include DELWP, BoM and VEWH.

However, this approach is very computationally intensive. Even more basic analyses can require hundreds or thousands of different model runs, which is prohibitively expensive using existing water resource models with single run-times measured in hours. In addition, UoM sought to use stochastic data generation to better represent the effects of alternate hydrological sequences beyond the specific sequence contained in historic records and significance of climate variability. The use of multiple stochastic replicates also increases the number of model runs that are required.

To overcome this challenge, UoM developed the SGEFM with the specific goal of reducing run times by addressing the complexity and detail in water resource modelling to retain those elements that represent key decision-making components and processes relevant to freshwater ecosystem outcomes. Another key design consideration for the model was flexibility to represent different adaptation or intervention options to support water resources planning under climate change.

The SGEFM was developed in consultation with DELWP, Goulburn Murray Water (GMW), and Goulburn Broken Catchment Management Authority. The result was a hybrid monthly-daily water resource model that closely follows water allocation frameworks and system operation, that has been specifically designed for contemporary system representation, including the management of environmental water and inter-valley transfers (IVTs) to the Murray system. The model has run-times in the order of fractions of a second, which enable large scenario assessments to be undertaken using multiple replicates of stochastic data. The model uses a monthly timestep to calculate water allocations and environmental and irrigation demands, and a custom disaggregation algorithm to model daily river flows that has been shown to outperform daily models in unregulated systems for assessing freshwater ecosystem outcomes (John et al., 2021b). The SGEFM been previously used to support the update of environmental flow recommendations in the lower Goulburn (Kaiela) River (Horne et al., 2020), to understand interacting stressors to freshwater ecosystem outcomes (John et al., 2022), and the effectiveness of different climate adaptation options in the Goulburn River (John et al., 2021a). The model is also fully compatible with the suite of twelve ecological models representing the fundamental and means objectives for environmental flows identified in the Goulburn River as part of the updated flow recommendations (Horne et al., 2020). Finally, the model can either be run using historic river inflows or using the stochastic data generation framework of Fowler et al., (2022), which enables statistical downscaling of climate change projections and assessment of the significance of climate variability on model outcomes.

The current scope and schematic of the SGEFM is shown in Figure 1.

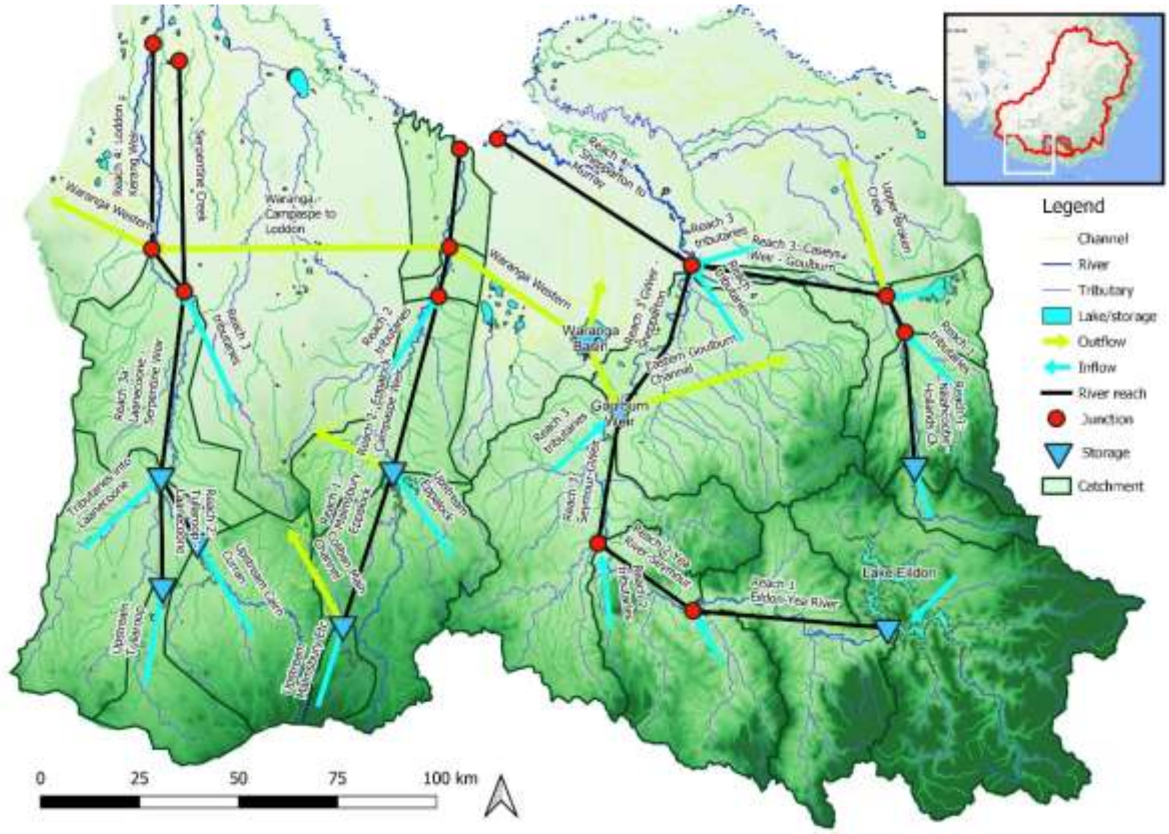

Figure 1. SGEFM scope and spatial representation. The model represents the connected Goulburn, Broken, Campaspe and Loddon Rivers and the operation of all major storages, and irrigation and environmental water entitlements. Note that the model was updated to include outputs at Molesworth and Trawool in the mid Goulburn.

4. Models updates to support constraints relaxation investigations

Stage 1A of the Victorian CMP included a modelling stocktake review which assessed modelling opportunities in the Goulburn and Murray Rivers, including the SGEFM (Sequana Partners, 2022). The stocktake review recommended the use of the SGEFM in a range-finding exercise to narrow constraints relaxation targets in the Goulburn River subject to model updates to better suit the specific needs of modelling constraints management. These included:

- Updates to the disaggregation algorithm to enable:
    - Daily outputs at multiple locations along the river (previously only available at McCoys Bridge)
    - Better representation of environmental flow release patterns, and pulses of summer IVTs as per the updated Goulburn River Operating Plan (Department of Environment Land Water and Planning, 2021a)
- Review and update of the annual and seasonal IVT delivery relationships to take advantage of new data and policies in reviews Goulburn Operating Plan and trade rule review
- Potential changes to Waranga Basin harvesting procedures to enable the delivery of high environmental flow components
- An alternate set of Goulburn River environmental demands that considers possible changes to environmental water use to meet Murray system needs. Note that the default modelling configuration

already includes IVTs to the Murray River and contemporary operation of the Goulburn environmental entitlement which includes some downstream benefits in the Murray.

4.1. Updates to disaggregation algorithm

Updates to disaggregation algorithm for multiple daily outputs and improvements to environmental flow freshes are documented in Appendix 1 - Disaggregation algorithm updates.

4.2. Review and update of IVT relationships

IVT updates are documented in Appendix 1 - IVT modelling and updates in the SGEFM.

4.3. Changes to Waranga Basin harvesting procedures

Waranga Basin harvesting arrangements are documented in Appendix 2 - Tributary harvesting to Waranga Basin in the SGEFM.

4.4. Alternate set of environmental demands to represent Murray River demands

The Murray demands scenario is documented in Appendix 3 - Murray demands scenario for Goulburn constraints modelling. Outcomes from the Murray demands scenario are discussed as part of the range-finding exercise below.

5. Range finding exercise

5.1. Purpose and objectives

Providing environmental water to the lower reaches of the Goulburn River can be achieved in two ways: through regulated releases at Lake Eildon which are passed down through to the lower Goulburn; and through ceasing the diversion of tributary inflows into Goulburn Weir (directed to Waranga Basin). Given this, there are potential interactions between constraints in the mid Goulburn and lower Goulburn reaches. For example, although relaxing lower Goulburn constraints is critical to providing high flow recommendations in this reach, relaxing mid Goulburn constraints can also help by supplementing tributary inflows from Lake Eildon.

The result of this is that different relaxation targets in the mid and lower Goulburn must be tested in combination, and that there are potentially a large range of possible options.

The purpose of the range-finding exercise is to narrow the range of potential constraints options in the mid and lower Goulburn River to some candidate specific flow scenarios that demonstrate potential ecological and hydrological benefits. These specific scenarios will then be assessed in more detail in subsequent stages of the Stage 1A CMP for benefits and risks.

5.2. Constraints scenarios considered

Constraint options are assessed at two locations: the “mid Goulburn” at Molesworth, downstream of the major Goulburn tributaries of the Acheron and Rubicon rivers; and the “lower Goulburn” at Shepparton, downstream of the confluence of the Goulburn and Broken rivers. The baseline (or existing constraints) scenario is modelled with constraints in the mid Goulburn of 10,000 ML/d, and the lower Goulburn of 9,500 ML/d.

Note that the range-finding exercise considers constrain relaxation options up to known minor flood levels along the river (Table 1; http://www.bom.gov.au/vic/flood/floodclass_north.shtml and https://data.water.vic.gov.au/). The lower Goulburn constraints are assessed at Shepparton and thus up to 30,800 ML/d limits are considered. The “mid Goulburn” constraints are assessed at Molesworth, which does not currently have a minor flood level. Thus, the range-finding exercise considers up to the minor flood level at Trawool (21,800 ML/d)[2].

The model also limits releases at Lake Eildon to below the Eildon minor flood level of 13,700 ML/d. For example, a scenario that considers up to 14,000 ML/d in the mid Goulburn would not allow the combined controlled Eildon

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[2] Given the absence of published flood class levels at Molesworth, other workstreams in Stage 1A of the Victorian Constraints Measures Program – i.e. the hydraulic modelling and asset impact assessment – will also be used to inform the feasible upper limit on constraint relaxation at this location.

release and tributary inflow upstream of Molesworth to exceed 14,000 ML/d, nor would it allow the controlled Eildon release alone to exceed 13,700 ML/d. Note there are additional restrictions in the model that do not allow the minor flood to be exceeded at Trawool and Seymour regardless of mid Goulburn constraint, but these restrictions are unlikely to be triggered as they would require very large inflows in the reaches between Molesworth and Seymour combined with very low inflows in the larger Acheron and Rubicon tributaries.

Table 1. Minor flood level at selected gauging sites along the Goulburn River.

Gauge number	Gauge location	Stage (m)	Flow rate (ML/d)
405203	Eildon	3	13,700
405201	Trawool	4	21,800
405202	Seymour	3.8	22,600
405200	Murchison	9	29,900
405204	Shepparton	9.5	30,800

5.3. Measures of system performance (key considerations)

The range-finding exercise measures outcomes through a suite of hydrologic metrics and ecological model results. With the exception of allocation reliability, these are assessed at McCoys Bridge in the lower Goulburn River. This is primarily due to existing ecological models only being available at this location.

The system performance metrics examined as part of the range finding exercise are described below.

Reliability of high reliability water shares issued in the Goulburn system

Reliability is defined as the percentage of years where full allocation is granted to high reliability water share holders. It affects all water allocations in the system including those for irrigators and the environment. In the bulk entitlement (Eildon – Goulburn Weir), there is a target for high reliability water shares to achieve 97% reliability based on the historic climate and reservoir inflows.

Shortfall in meeting environmental flow recommendations

This is the average annual deficit between environmental flow recommendations and the actual flow in the river. This focuses on the Kaiela section of the river downstream of Goulburn Weir (near McCoys Bridge gauging station) and uses the latest flow recommendations. Larger shortfall volumes generally mean environmental water objectives are not being met. However, as this is just based on total volumes of water, it does provide information regarding the consequences of missing certain flow components with different relative priorities.

Constrained environmental water delivery

Water that has been allocated to environmental accounts, planned for priority deliveries, but cannot be delivered due to constraints. Note that this water is not "lost," as unused water can be carried over and used later in the season for lower priority flow components. But it does represent water that would have otherwise been used to deliver priority flow components such as overbank flows.

Ecological model outputs

In addition, ecological outcomes are assessed using ecological models developed as part of the Kaela (Lower Goulburn River) environmental flows assessment. The flows assessment identified a number of fundamental objectives for environmental flows including objectives for: opportunistic fish, periodic fish, equilibrium fish, floodplain vegetation, mid bank vegetation, littoral vegetation, turtles and platypus. Ecological models are available for each of these endpoints. In addition ecological models are also available for a number of processes that support these endpoints: bank stability, instream production, geomorphic complexity and macroinvertebrates. Some models have feedbacks in that the outcomes of certain models form the inputs of others (such as macroinvertebrate abundance informing fish recruitment and survival). These endpoints and the models themselves are described in further detail in Horne et al. (2020).

These models take the form of conditional probability networks and include consideration of uncertainty in parameterising relationships between ecological processes (informed through expert elicitation and data integration where possible). One consequence of this uncertainty is a relative insensitivity in final model outputs to changes in inputs. To overcome this, and to better relate the significance of changes in outputs to the distribution of baseline variation, stochastic data is used to produce multiple different sequences of hydrologic inputs. Output distributions under some changed parameters (i.e. relaxed constraints) are then compared to the output distribution under baseline conditions following the method of Nathan et al. (2019). A "stress index" is calculated based on the proportion of shared area between the two distributions, where:

- -1 represents conditions wholly worse than experienced under the baseline,
- 0 represents no change, and
- +1 represents conditions wholly better than the baseline (see example below).

This approach also allows direct comparison across the twelve ecological models, despite their differences in sensitivity to flow and individual dynamics.

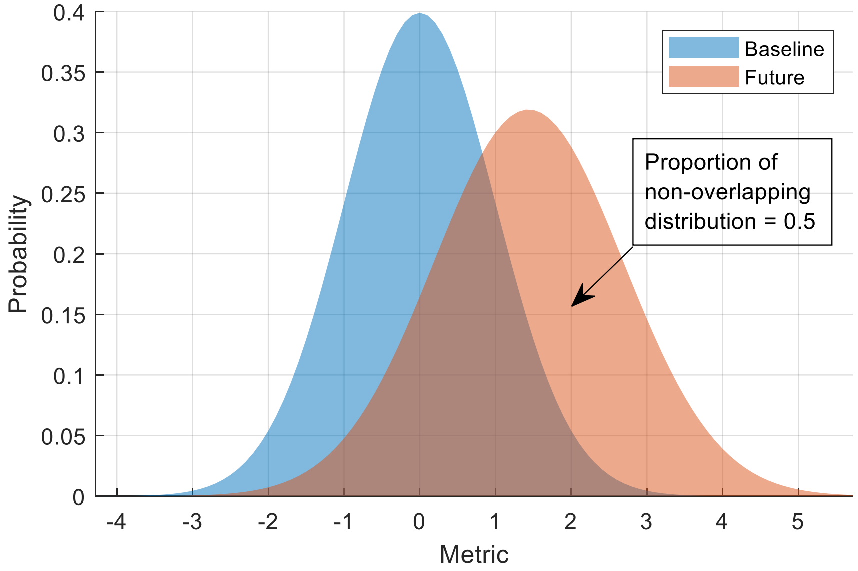


Figure 2. Illustration of how the stress index is calculated. It is based on the proportional shared area between the baseline and future distributions informed by 100 replicates of stochastic data. In this case, the stress index is 0.5. The sign of the index is determined by whether the median outputs of the future distribution are considered worse (i.e. poorer ecological condition) than the median outputs of the baseline distribution

5.4. Methodology

Constraints scenarios are assessed for 100 different combinations of constraint options in the mid and lower Goulburn. This includes 10 gradations for each of the mid and lower Goulburn constraint, which are linearly spaced from baseline conditions up to the maximum constraint (see Figure 3).

Each constraints scenario is assessed using the SGEFM. The modelling framework includes the following steps:

- Stochastic climate data for monthly temperature and precipitation are generated over the Goulburn river basin. These are input into rainfall-runoff models to produce tributary and storage inflows (see Fowler et al., (2022) for more details).
- The model is run to produce a timeseries of daily flows. Flows are input into the twelve ecological models which produce an annual projection of ecological outcomes.

    - Slightly different sequences are used for hydrological metrics and ecological models. Hydrological metrics use 30 replicates of 50 year sequences. These longer sequences are necessary for estimating metrics such as system reliability. The outputs reported in subsequent figures are the mean across the 30 replicates. Ecological models use 100 replicates of 20 year sequences instead. More replicates are used in this case to better characterise baseline and constraints scenario distributions.
- For all constraints scenarios, an example future climate scenario with 10% decrease in annual precipitation and 2 °C increase in temperature (typical of projections from a moderate emissions scenario around the year 2065) is included to test robustness. This is applied using a change-factor method, where the baseline stochastic rainfall series is multiplied by 0.9, and temperature series has 2 degrees added. This is designed to test (at a high level) whether the outcomes from the range finding exercise are consistent in a drier climate. Note that a more detailed climate change vulnerability analysis is undertaken for selected constraints scenarios.

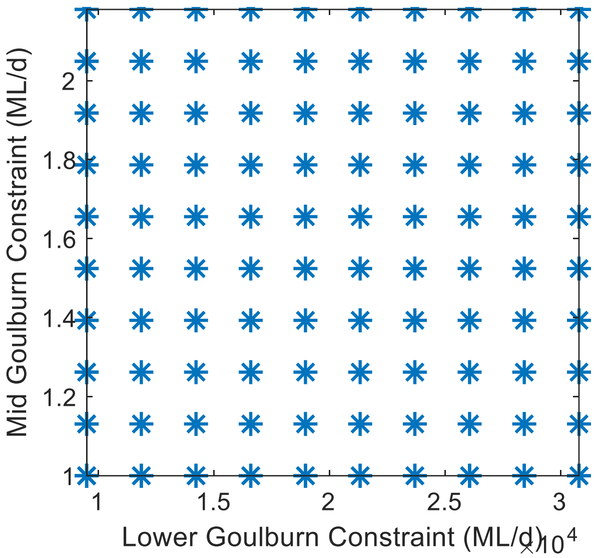


Figure 3. Combination of constraint options investigated in the range-finding exercise. 10 gradations for each of the mid and lower Goulburn are assessed, for a total of 100 scenarios. The baseline scenario is in the bottom left corner.

Much of the presentation of results in the range finding exercise follows the style of Figure 3 above. That is, the x-axis shows the constraint option in the lower Goulburn, and the y-axis shows the constraint option for the mid Goulburn. Hydrological metrics or ecological model outputs can be read by the coloured contours in each figure.

5.5. Outputs – hydrologic metrics

The three key hydrologic metric outputs for the range-finding exercise are shown in Figure 4. It was found that there was limited sensitivity of allocation reliability to different constraint options. This is evident through the solid colour (lack of contours) in the allocation reliability panel (left) in Figure 4. Note that for environmental water shortfalls and constrained delivery volumes (the middle and right panel), the improvement relative to the baseline scenario is given. Environmental water shortfalls were 130 GL/year, and constrained delivery was 178 GL/year, in the baseline scenario.

Even under the maximum constraints options tested here, there is approximately 60 GL/year (130 under baseline less approximately 70 in upper right corner of panel) of shortfall that cannot be reduced. This is due to shortfalls being sensitive to processes beyond constraints, such as water supply and variability, where there are some years with naturally low water allocations or tributary inflows that contribute to environmental shortfalls. Shortfalls can be reduced by either relaxing constraints in the mid Goulburn or lower Goulburn reaches. However, the rate of benefits in reducing shortfalls decreases if focusing on one river reach. In other words, better outcomes are achieved with commensurate constraints relaxation in both reaches. The maximum shortfall reduction was achieved with a combination of constraints of approximately 20,000 ML/d in the lower Goulburn and 14,000 ML/d in the mid Goulburn (darkest blue region of the panel).

Focusing on the constrained delivery panel (right), the ability to deliver priority (high) flow components is more sensitive to the lower Goulburn constraint than the mid Goulburn constraint. Unlike environmental water shortfalls, constrained delivery volumes can be reduced to near zero with high constraint thresholds (178 in baselines less ~170 in upper right corner of the panel). There is also a diminishing rate of return in reducing constrained delivery volumes when relaxing constraints in a single reach. Generally, this becomes more apparent when relaxing the lower Goulburn constraint past ~20,000 ML/d without also relaxing the mid Goulburn constraint. The maximum reduction in constrained delivery volume was achieved with approximately 25,000 ML/d in the lower Goulburn and 14,000 ML/d in the mid Goulburn, or ~30,000 ML/d in the lower Goulburn and 13,000 ML/d in the mid Goulburn.

For both environmental water shortfalls and constrained delivery, it is likely that the insensitivity seen in relaxing the mid Goulburn constraint beyond 14,000 ML/d is due to the minor flood level restriction at Eildon in the SGEFM. This limits Eildon releases to 13,700 ML/d maximum even in scenarios where the mid Goulburn constraint is significantly higher.

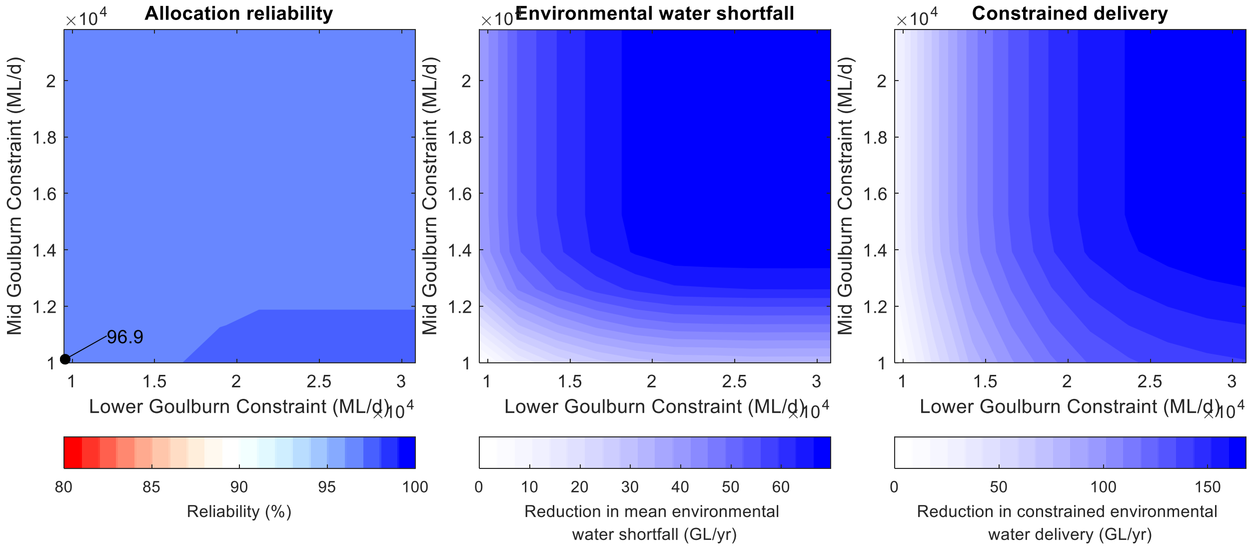


Figure 4. Hydrologic metrics output from the range-finding exercise under baseline climate. For environmental water shortfalls and constrained delivery volumes, the improvement relative to the baseline scenario is given. Baseline shortfalls were 130 GL/year, and constrained delivery was 178 GL/year.

Output metrics for environmental water shortfalls and constrained delivery volumes under the example drier future climate scenario are shown in Figure 5. The intent here is to assess whether the relationships evident in Figure 4 are consistent across a drier climate. The general patterns of responses between environmental water shortfalls and constrained delivery are consistent between the current and drier climate scenario, in that the shape of contours and approximate rate of benefits is similar between Figure 4 and Figure 5. This suggests that relaxing constraints will still deliver benefits under a drier future climate. Selected constraint options are the focus of more detailed climate change vulnerability analysis in following sections.

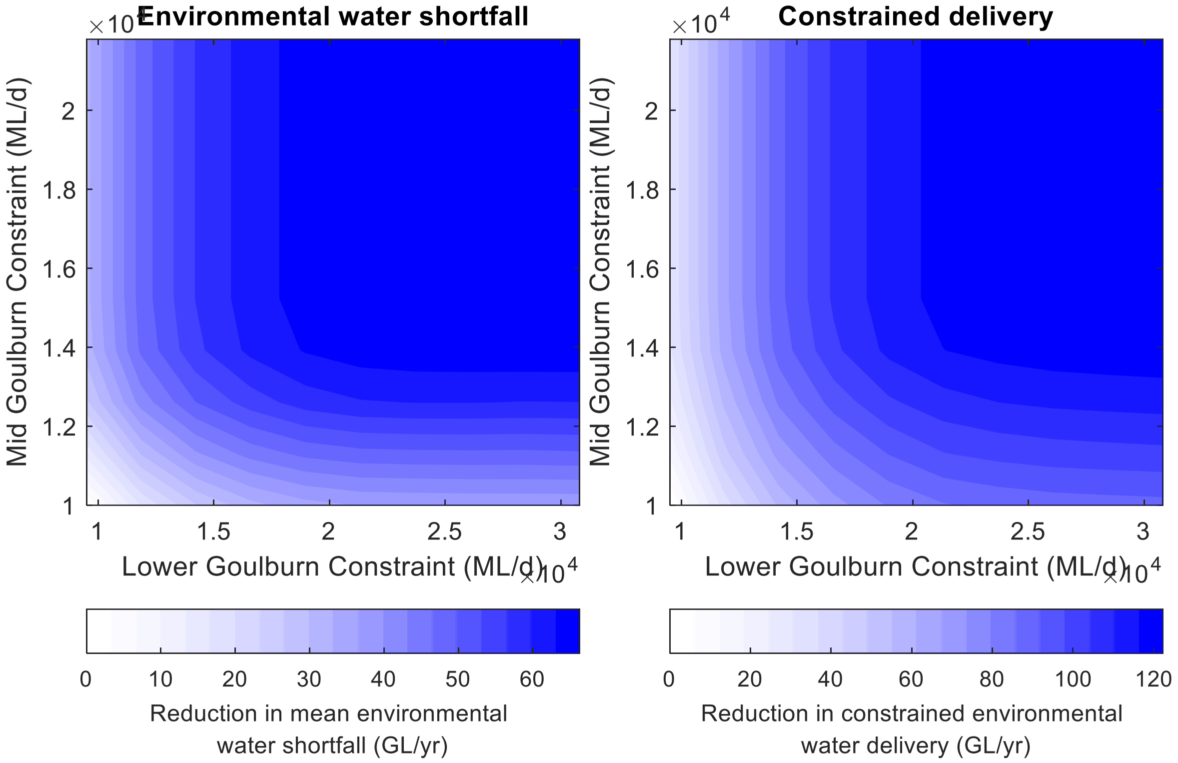


Figure 5. Hydrologic metrics output from the range-finding exercise under example drier climate. The improvement relative to the baseline scenario (given drier climate) is shown as per Figure 4.

5.6. Outputs – ecological models

The outputs of all twelve ecological models for the range finding exercise is shown in Figure 6. The stress index formulates responses relative to the baseline scenario. Hence, for different constraint options, the outcomes suggest whether there will be an improvement in ecological condition (blue regions) or potential degradation (red regions) relative to the baseline. It is important to note that some ecological models respond poorly to higher flows. For example, any increase in river flows can contribute to poorer outcomes in the bank stability model through increased slumping and notching. There are a range of assumptions inherent in the derivation and dynamics of the ecological models. A full explanation of these is given in Horne et al. (2020).

This analysis as part of the range-finding exercise only reports on the total modelled ecological outcomes under various constraint options. It does not delve into detail around the specific ecological processes that influence positive or negative outcomes. Rather, the purpose is to highlight constraint options that appear attractive in delivering overall benefits, which will be assessed in more detail at a later stage of the project.

The range of variation under the baseline scenario informs the magnitude of the stress index. For example, a model that is relatively invariable through time will show a higher stress index for a given change under a particular constraint option. Most models show improved outcomes under relaxed constraints. There are significant benefits for geomorphic complexity and all fish models. Floodplain vegetation shows minor improvement for lower Goulburn constraints of 20,000 ML/d. There are key threshold responses in some models. Instream production shows generally poorer outcomes unless constraints are relaxed past 20,000 ML/d in the lower Goulburn, where outcomes dramatically improve. Conversely, platypus outcomes show benefits up to around 22,000 ML/d, with a risk of poorer outcomes above this level. Fish models and midbank vegetation show improvements with constraint relaxation in the mid Goulburn as well as lower Goulburn reaches, similar to results in the previous hydrologic metrics. The best outcomes for these models are generally achieved with mid Goulburn constraint of at least 12,000 ML/d.

Some models show the potential for poorer outcomes under relaxed constraints (bank stability, littoral vegetation, turtle population). This is because some models are sensitive to higher flows or have dependencies (i.e. littoral vegetation and turtles are linked to the bank stability model outcomes).

Figure 7 shows the same ecological model outputs for the example drier future climate scenario. Note that in Figure 7, the stress index is calculated relative to the baseline climate scenario. Climate change presents significant risks for ecological outcomes, evidenced by the high negative stress indexes in most models. However, even though most model outcomes are poor under the drier climate, constraints relaxation does not exacerbate poor conditions (with the exception of the turtles for lower Goulburn constraints between ~13,000 and 20,000 ML/d). Rather, relaxing constraints reduces the impact of climate change for many models (seen through a reduction in negative stress scores when moving from left to right in the panels). This represents possible climate change adaptation benefits of relaxed constraints, which will be further explored in subsequent sections of this report.

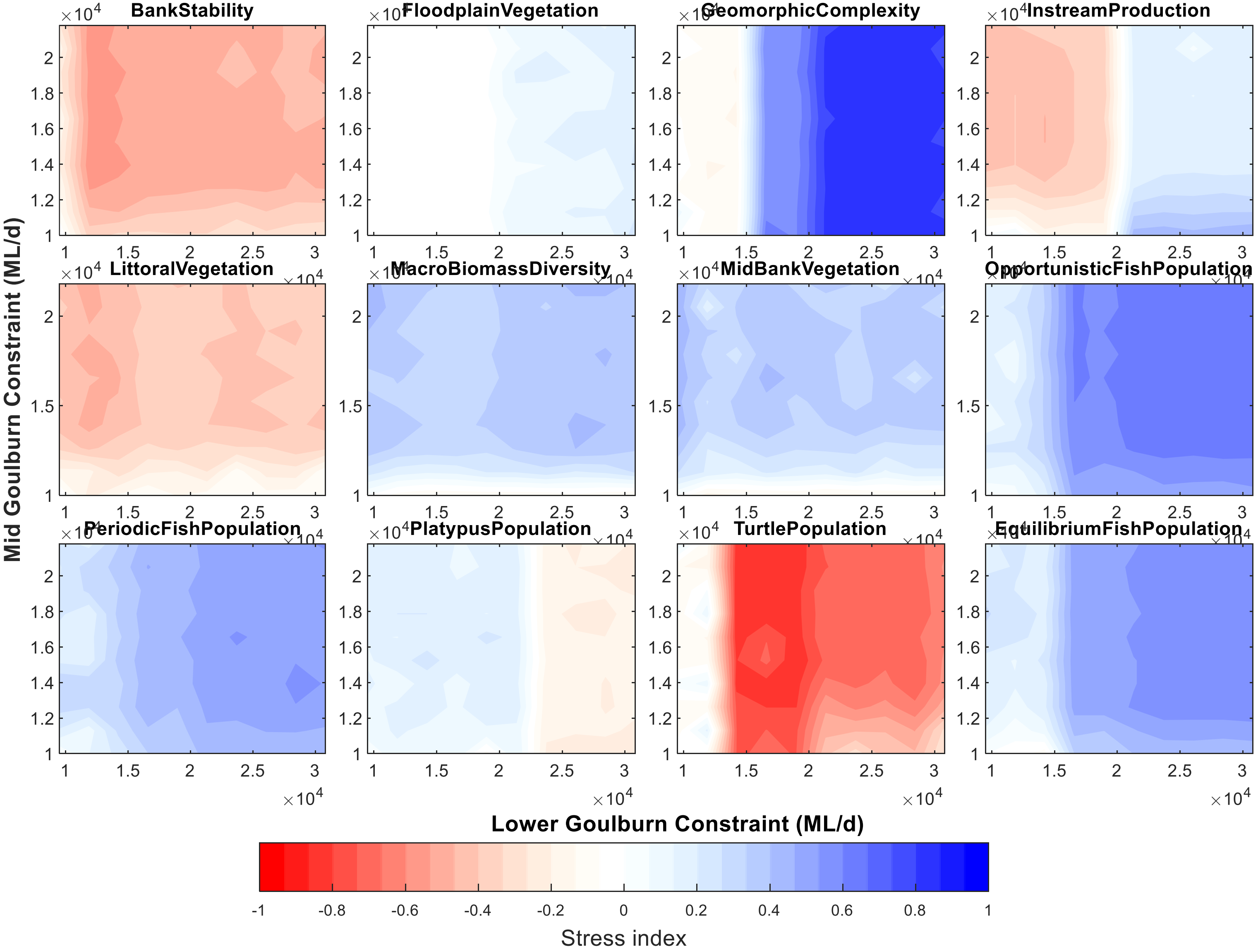

BankStability
FloodplainVegetation
GeomorphicComplexity
InstreamProduction
LittoralVegetation
MacroBiomassDiversity
MidBankVegetation
OpportunisticFishPopulation
PeriodicFishPopulation
PlatypusPopulation
TurtlePopulation
EquilibriumFishPopulation
Mid Goulburn Constraint (ML/d)
Lower Goulburn Constraint (ML/d)
×10^4
1
1.2
1.4
1.6
1.8
2
1.5
2.5
3
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Stress index

Figure 6. Individual ecological model outputs for the twelve ecological models for the range finding exercise. The stress index shows modelled ecological benefits (blue area) or disbenefits (red area) relative to the baseline scenario.

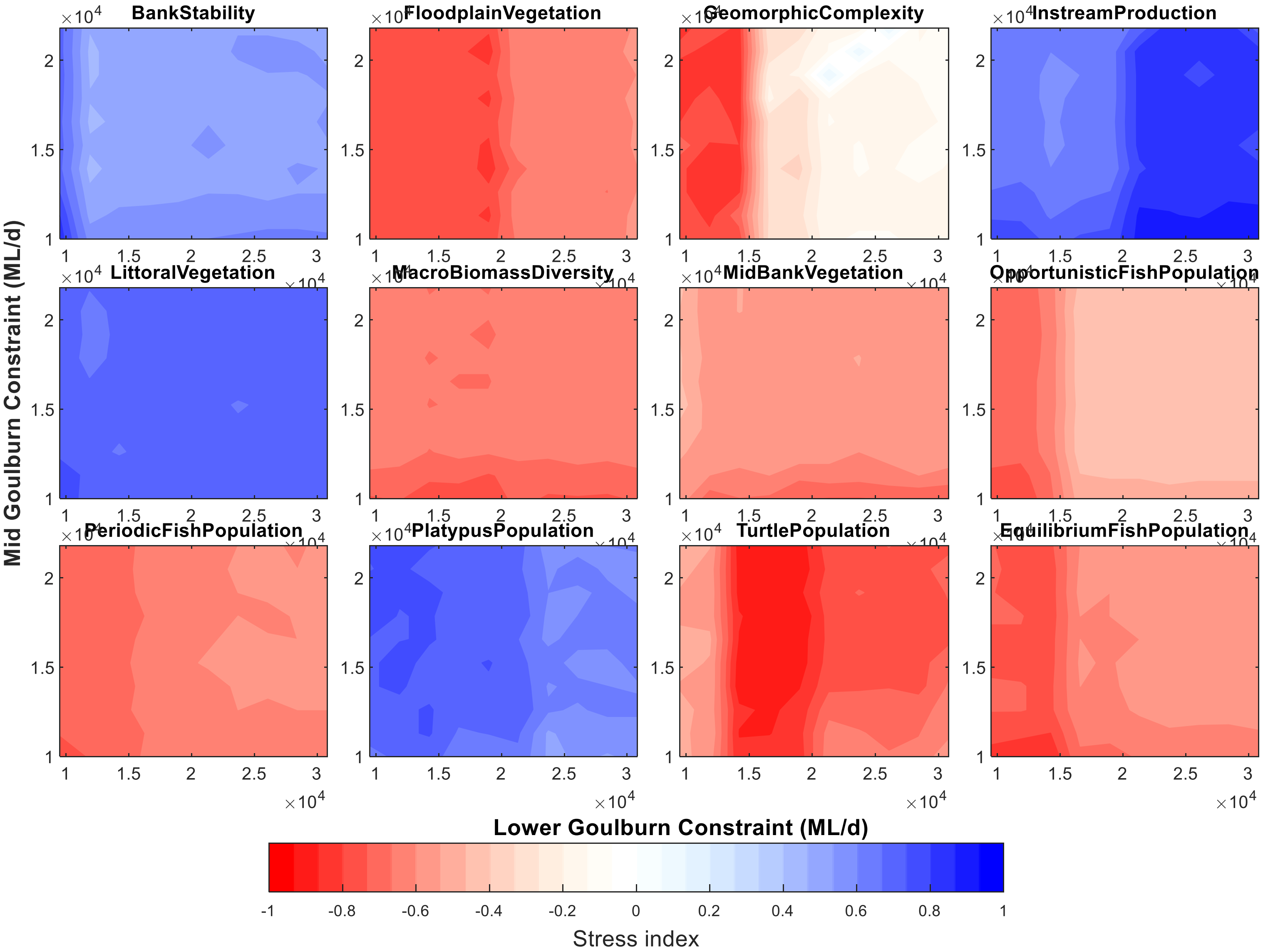


Figure 7. Individual ecological model outputs for the twelve ecological models for the range finding exercise and example drier future climate. The stress index shows modelled ecological benefits (blue area) or disbenefits (red area) relative to the baseline scenario and baseline climate.

Figure 8 shows the mean ecological outcomes calculated across the nine fundamental objectives in the Kaiela flow recommendations. The effects of the three means objectives are captured in the response of the fundamental objectives, as they form inputs into the other nine models. This is intended to show, at a relatively high level, regions of the constraint options that provide overall ecological benefits. There are clear thresholds in overall ecological outcomes. Figure 8 shows threshold responses at lower Goulburn constraints of ~14,000 ML/d and 21,000 ML/d. Model results suggest minor benefits from ~16,000 ML/d to 20,000 ML/d in the lower Goulburn, with a stronger response once lower Goulburn constraints exceed 20,000 ML/d. There is an apparent insensitivity to mid Goulburn constraints when assessing the mean outputs, especially beyond about 12,000 ML/d. However, this is partially due to differential responses in individual models being smoothed out when taking the mean. In other words, because some models respond well to relaxing the mid Goulburn constraint, and some models respond poorly, these offset each other when taking the mean across all models.

Generally, the best overall outcomes occur when the lower Goulburn constraint is relaxed beyond 20,000 ML/d, and the mid Goulburn constraint is relaxed to 12,000 ML/d. There is little apparent benefit to relaxing mid Goulburn constraints beyond 12,000 ML/d according to the mean ecological model outputs. **It is important to note however that these results are based on ecological outcomes for the Lower Goulburn only, and do not consider environmental benefits to the mid Goulburn itself.** This also generally applies to the individual ecological model outputs in Figure 6.

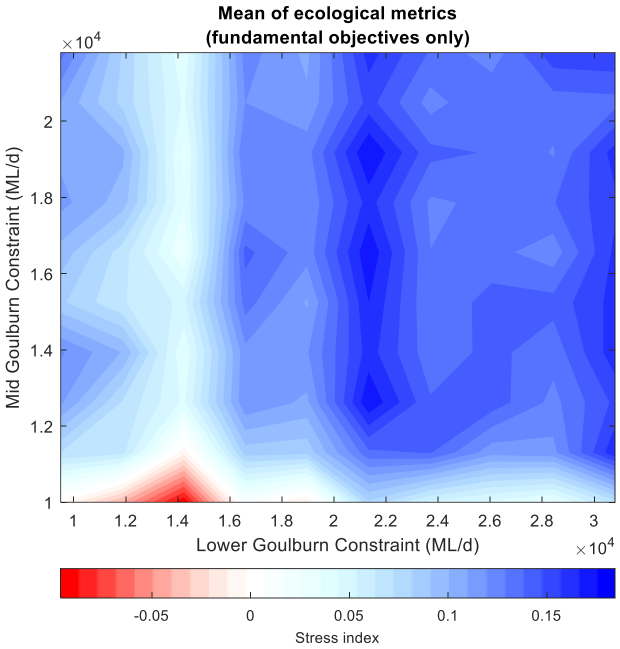


Figure 8. Mean output of the nine models that form fundamental objectives in the Kaiela flow recommendations (excludes bank stability, geomorphic complexity and instream production), showing general regions of potential overall ecological benefits and risks.

The mean ecological outputs are also shown for the example drier future climate in Figure 9. Here, the potential for constraints relaxation to offer climate change adaptation benefits is clear. Constraints relaxation can significantly (although not totally – roughly up to a 50% reduction in the stress index) offset poor ecological outcomes due to climate change. Constraints options above 20,000 ML/d in the lower Goulburn reduce the mean stress index from climate change by approximately 33% (-0.45 to -3), however the stress index is a non-linear metric as it is based on system variability.

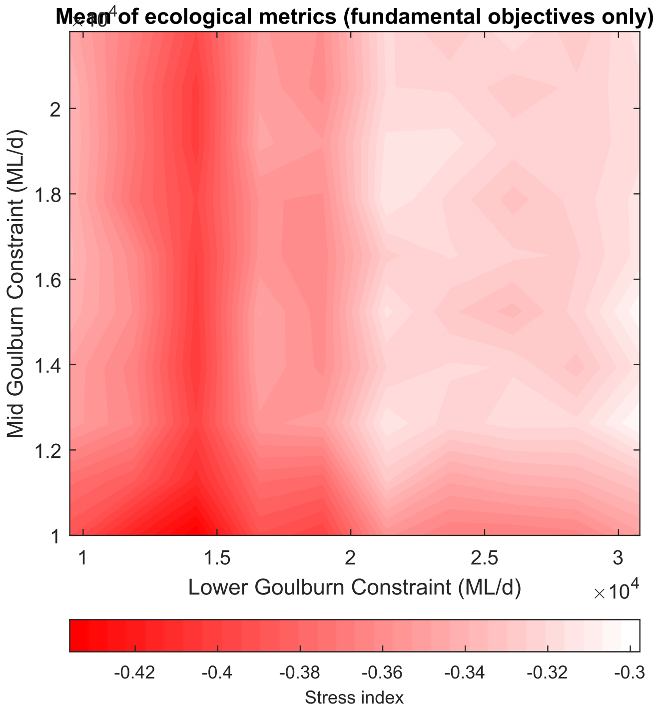


Figure 9. Mean output of the nine models that form fundamental objectives in the Kaiela flow recommendations under example drier future climate. The stress index is calculated relative to the baseline under existing climate conditions, which is why it begins as negative in the lower left corner of the panel.

5.7. Recommendations – constraints scenarios of interest for further analysis

A synthesis of the previous results provides the following outcomes for preferred constraints relaxation targets:

- Analysis of hydrologic metrics shows relaxing lower Goulburn River constraints is more effective in providing higher flow components. However, there are diminishing returns in either reducing constrained water delivery or environmental water shortfall. Especially beyond 20,000 ML/d in the lower Goulburn, constraint relaxation in the mid Goulburn should be considered.
- Ecological outcomes as inferred from ecological model results benefit more from constraints relaxation in the lower Goulburn River. This is linked to the provision of larger overbank flows. Overall outcomes become greater when lower Goulburn constraints are > 20,000 ML/d.
- There are slight differences between the results looking at hydrologic metrics and ecological model outcomes. This is because neither is a perfect representation of ecological benefits.
- Constraints relaxation has the potential to mitigate impacts of a drier climate, both in ecological outcomes and hydrologic metrics.

This analysis has recommended further investigation of the following constraints relaxation targets:

Current constraint (10,000 ML/d) in mid Goulburn, 17,000 ML/d in lower Goulburn

- This was generally the lowest constraint option that still provided overall ecological benefits and avoids diminishing returns from hydrologic metrics

Current constraint (10,000 ML/d) in mid Goulburn, 21,000 ML/d in lower Goulburn

- This scenario avoids constraint relaxation in the mid Goulburn but may suffer from diminishing returns in ecological benefits.

12,000 ML/d in mid Goulburn, 21,000 ML/d in lower Goulburn

- This provided greater modelled ecological benefits just above apparent thresholds, and substantial reductions in environmental water shortfall and constrained environmental water delivery.

14,000 ML/d in mid Goulburn, 25,000 ML/d in lower Goulburn

- While the rate of benefit for relaxing constraints reduces after the previous scenario, the ecological models which rely on overbank flows improve beyond 20,000 ML/day. The best outcomes for these models is from higher flows. This scenario generally provides an ‘upper bound’ of possible flows which can be managed within known minor flood levels and may provide some extra benefits in the mid Goulburn which were not assessed as part of the range-finding exercise.

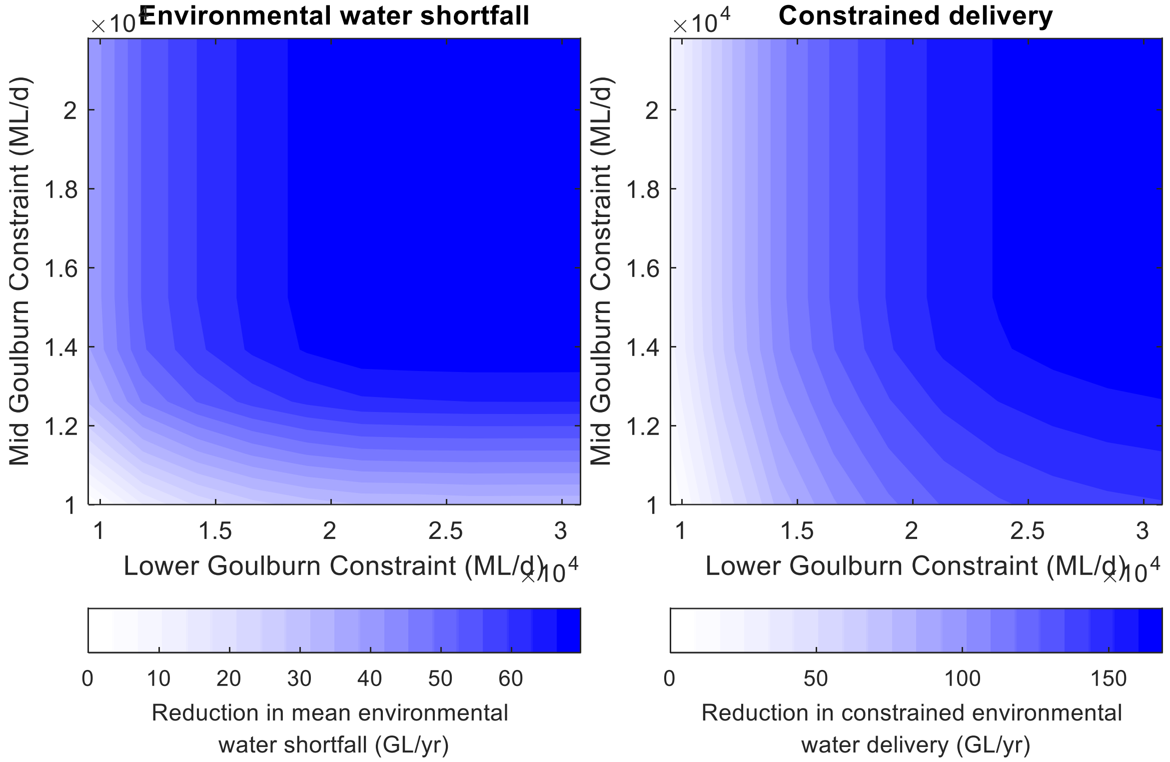
5.8. Alternate Murray River demands scenario

The alternate Murray River demands scenario is included to test whether the outcomes from the range-finding exercise are robust when considering possible changes to management of the Commonwealth Environmental Water Office’s entitlement.

Comparisons of hydrological and ecological outputs between each scenario are shown in Figure 10 and Figure 11. In general there were very limited differences between outcomes. The Murray scenario has slightly higher benefits in reducing constrained delivery volumes. Note the Murray scenario has higher baseline environmental water shortfall due to higher environmental flow demands. The Murray scenario also has slightly higher (~1%) baseline constrained delivery volumes.

For the ecological models, the Murray scenario has slightly higher ecological benefits across range of tested constraints relaxation targets. This was driven by higher benefits to macroinvertebrates, instream production, and geomorphic complexity (not shown). Nonetheless, the outcomes do not change the original recommendations from the range-finding exercise.

Default scenario



Murray demands scenario

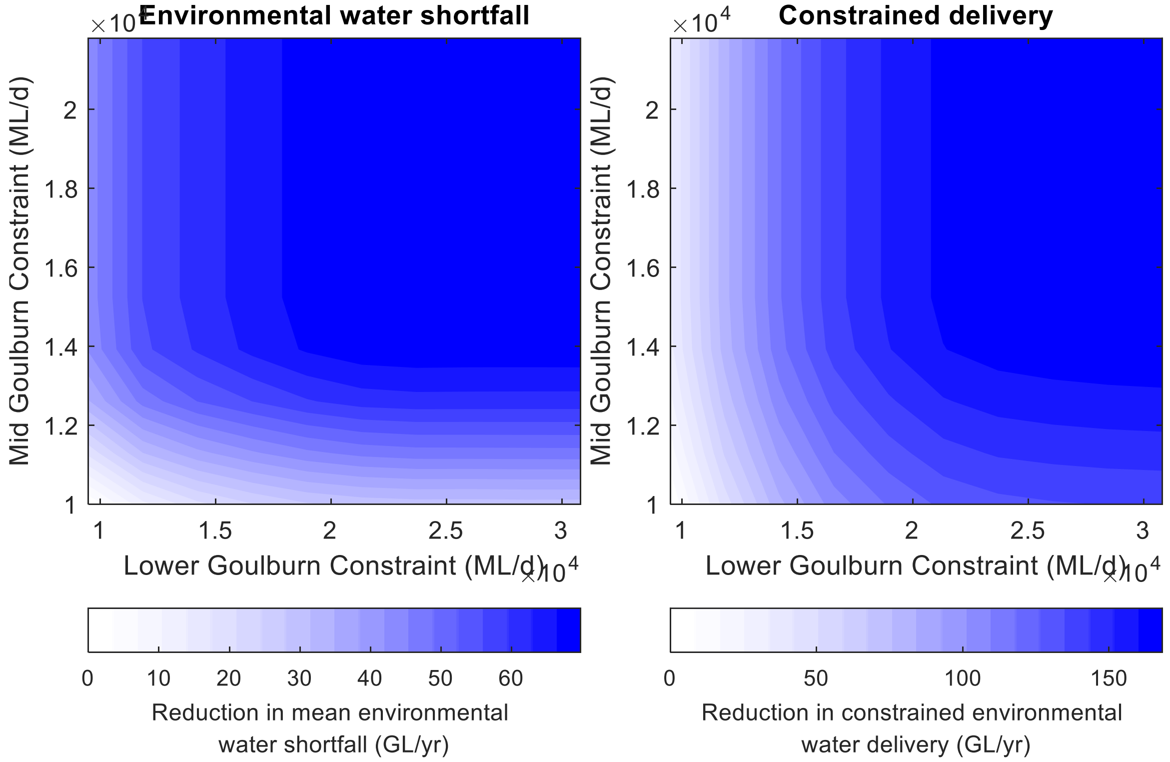
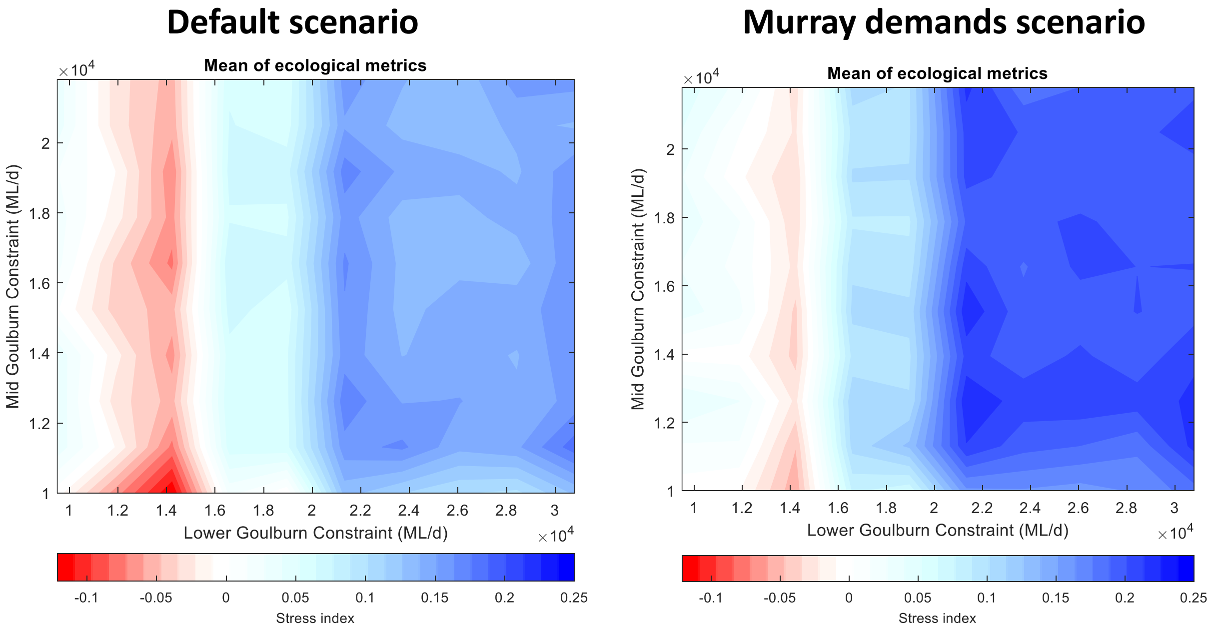


Figure 10. Default scenario vs. alternate Murray demands scenario hydrologic metrics. The general patterns and recommendations from either scenario are consistent.



Default scenario

Murray demands scenario

Figure 11. Default scenario vs. alternate Murray demands scenario mean ecological model outputs. Note that the left panel colour limits have been rescaled from Figure 8 a) to be consistent with the right panel in this figure.

6. Climate change vulnerability analysis of selected scenarios

The SGEFM and stochastic data framework allows for comprehensive climate change vulnerability analysis to be undertaken. The vulnerability-based method is used due to the significant uncertainty in future climate projections (see Figure 12). However, climate model outputs generally point to drying conditions in the Goulburn River. The purpose of this analysis is to ascertain robustness of benefits of constraints relaxation across a large range of future climates, and offer further insight into climate change adaptation benefits.

However, due to current methodological limitations, this must be undertaken one-at-a-time for particular constraints options. Here, the recommended constraints options from the range-finding exercise are subject to more detailed climate change vulnerability analysis.

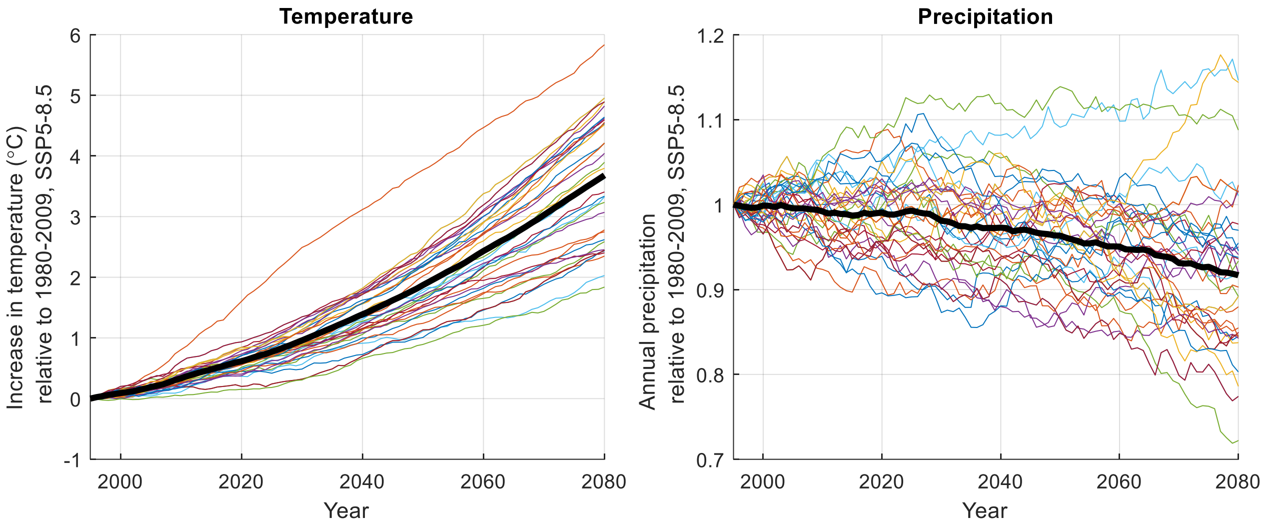


Figure 12. Climate model projections for annual precipitation and temperature for the Goulburn River basin for SSP5-8.5. Each coloured line is a CMIP6 model projection. The bold black line is the multi-model-mean projection.

6.1. Methodology

SGEFM inputs are generated following the same method as the range-finding exercise. However, instead of systematically varying mid and lower Goulburn constraints, 100 different scenarios of plausible future climate are simulated. This includes generating 10 combinations for each of average annual precipitation and temperature. More details on the method for generating data and perturbing climate series is given in Fowler et al. (2022). The bounds for generating precipitation and temperature change factors are informed by the spread of CMIP6 climate model projections over the Goulburn River basin, using emissions scenario SSP5-8.5. This analysis extends these bounds a short way beyond the envelope of climate model projections given uncertainty in climate model outputs, and to highlight any extra vulnerabilities. Precipitation and temperature bounds, and CMIP6 model outputs are described in Table 2. CMIP6 results are shown aggregated over the Goulburn River basin, and have been downscaled and bias corrected following the method outlined in (John et al., 2021a).

Table 2. Range of climate variables tested, and expected range from CMIP6 climate models.

Climate variables	Description	Lower bound	Upper bound	Number of gradations	Expected range from climate models (SSP5-8.5, 2065)[1]
Long-term average rainfall	Factor of multiplication to mean long-term average rainfall	0.7	1.15	10	0.8 to 1.12
Temperature	Addition to maximum monthly surface air temperature	0	4	10	1.2 to 3.7

[1] Excludes one very hot projection in Figure 12.

6.2. Hydrologic metrics

Existing system conditions results (current constraints) are shown in Figure 13. This shows how allocation reliability, environmental water shortfall, and constrained delivery volumes vary with climate change. Note the x and y-axes are identical for all three plots (and subsequent plots). Climate model outputs are plotted over failure surfaces for two time periods (2040 and 2065) and two emissions scenarios (SSP5-8.5 and SSP2-4.5). Also highlighted is the system performance for the baseline climate (0,0).

The system is overall, highly sensitive to changes in climate. Environmental water shortfall volumes increase with a drying climate, as tributary inflows and water entitlements decrease. Constrained delivery decreases with a drying climate, since this quantity represents allocated (but undeliverable) water. However, there is still a substantial volume of allocated environmental water that cannot be delivered for priority environmental flow components due to constraints even for a considerably dry climates.

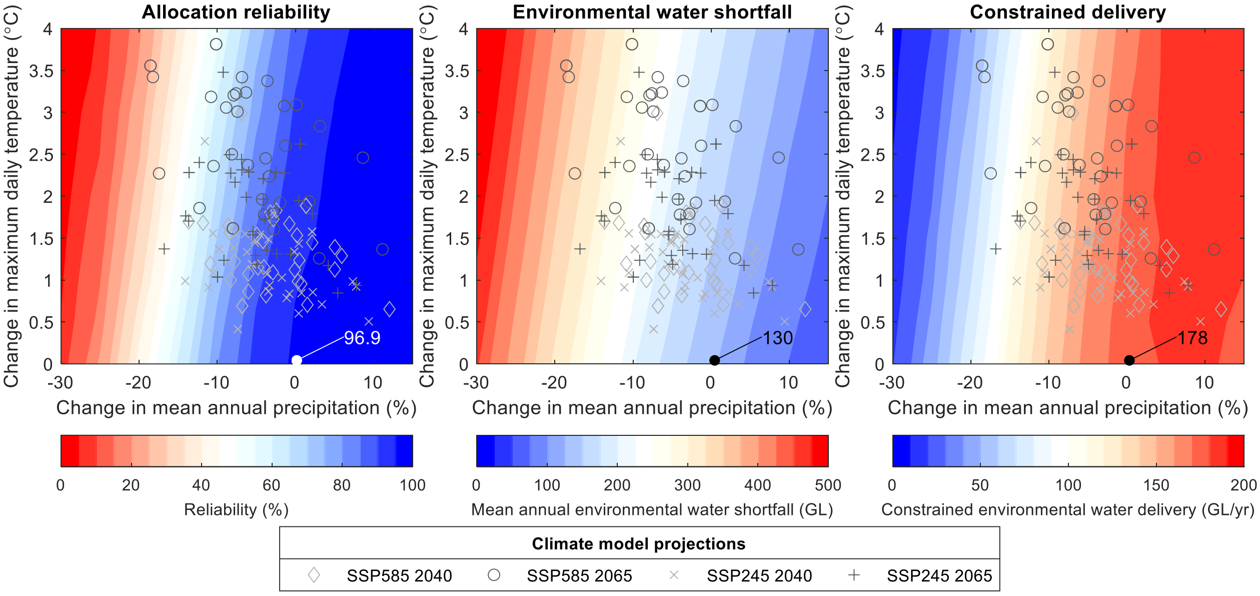


Figure 13. Baseline constraint (current conditions) climate change vulnerability for key hydrologic metrics. Climate model projections are overlaid onto the axes for precipitation and temperature change.

The four different constraint options are presented in Figure 14 to Figure 17. These plots present results relative to the baseline values in Figure 13. Here, any region in blue shows an improvement from baseline conditions. There are some limited apparent increases in system reliability under drier climates when relaxing constraints (roughly similar magnitude for each constraint option). However, this is not the focus of this assessment and could be investigated in more detail in later stages.

For the first option, relaxing constraints to 17,000 ML/d in the lower Goulburn delivers consistent benefits across a range of future climates. Environmental water shortfall reductions are strongest under a moderately dry future climate. This suggests that this constraint option will deliver even greater benefits under a drier future climate. However, the total environmental water shortfall may still remain high.

The second option (21,000 ML/d lower Goulburn, 10,000 ML/d mid Goulburn) delivers similar benefits to the first option across the variable climate, with slightly better improvements in constrained delivery volumes. This generally agrees with the outcomes in Figure 4 above, where there were diminishing returns in reducing environmental water shortfalls unless there was commensurate constraint relaxation in the mid and lower Goulburn River.

For the third option (21,000 ML/d lower Goulburn, 12,000 ML/d mid Goulburn), similarly as before, relaxing constraints delivers consistent benefits under a range of future climates. There is a notable stronger response in benefits compared to previous scenario, especially for environmental water shortfall reductions. For the current climate, reductions in environmental water shortfall are ~100% higher, and reductions in constrained delivery ~40% higher than the first option. Residual constrained delivery is small compared to the baseline constraints (38 GL vs. 178 GL in the baseline).

The fourth option (25,000 ML/d lower Goulburn, 14,000 ML/d mid Goulburn) shows the largest benefits in hydrologic metrics across a range of climate.

All constraint options deliver benefits across a relatively wide range plausible climates consistent with climate model projections. Hence, constraint relaxation is likely to offer robust climate change adaptation benefits.

However, for very dry future climates (reductions in precipitation of 20% or more) that benefits of constraints relaxation begin to disappear. However, it is worth noting that this would likely be a very different river operating environment with such dry conditions compared to contemporary management.

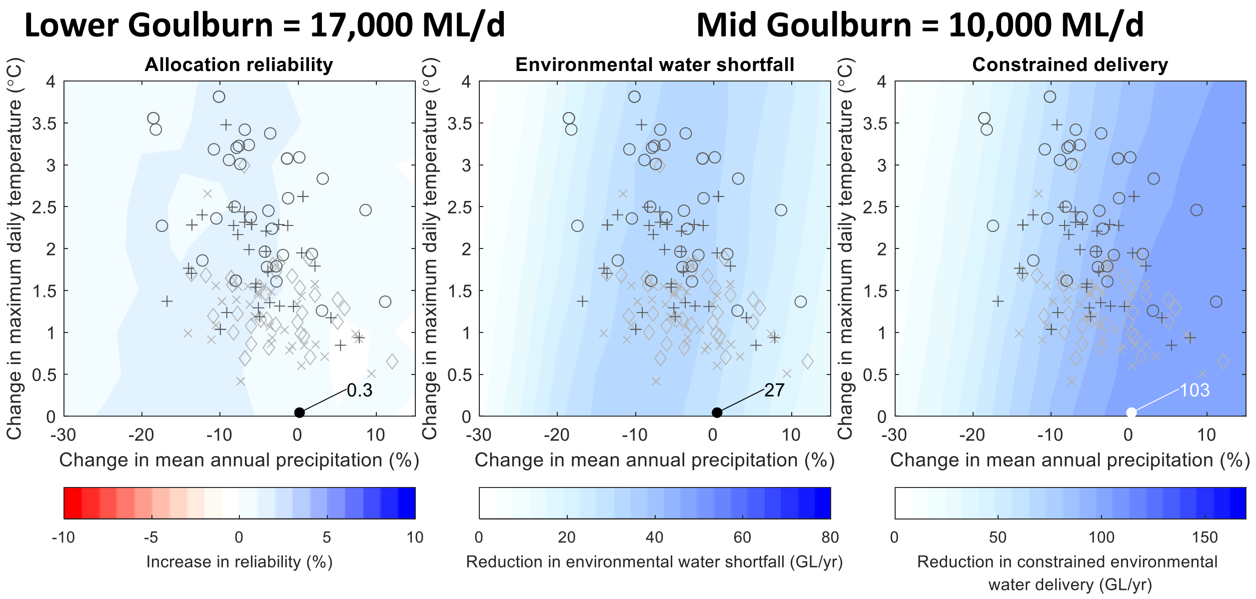


Figure 14. Climate change vulnerability analysis for constraint option of 17,000 ML/d in lower Goulburn and 10,000 ML/d in mid Goulburn. Results are shown relative to the baseline in Figure 13.

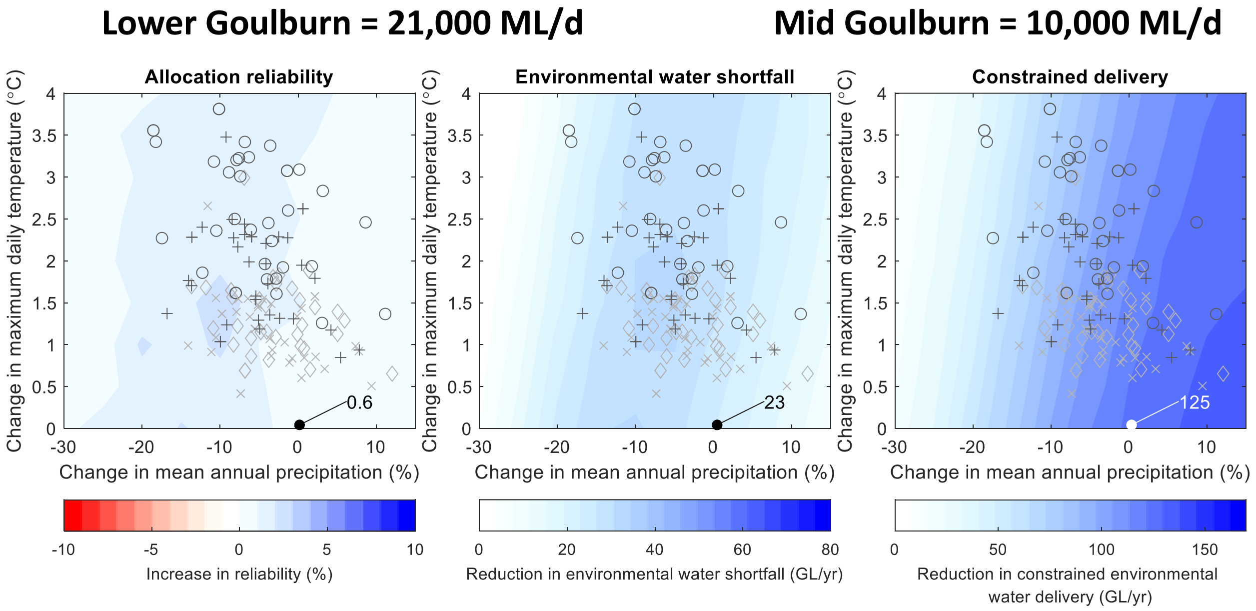


Figure 15. Climate change vulnerability analysis for constraint option of 21,000 ML/d in lower Goulburn and 10,000 ML/d in mid Goulburn. Results are shown relative to the baseline in Figure 13.

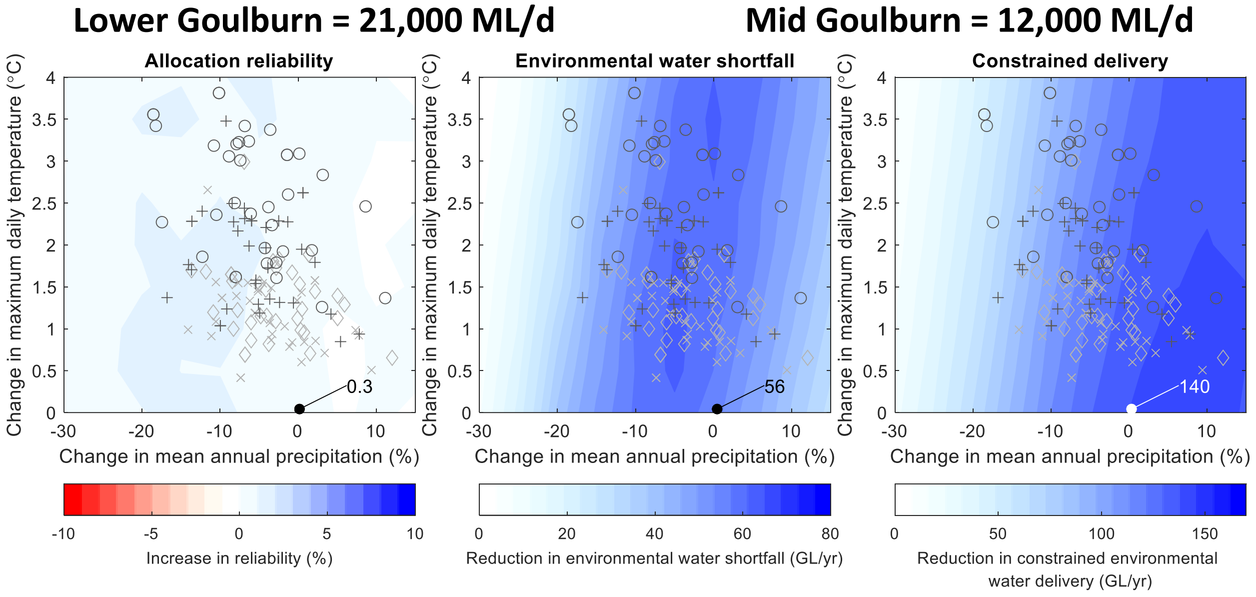


Figure 16. Climate change vulnerability analysis for constraint option of 21,000 ML/d in lower Goulburn and 12,000 ML/d in mid Goulburn. Results are shown relative to the baseline in Figure 13.

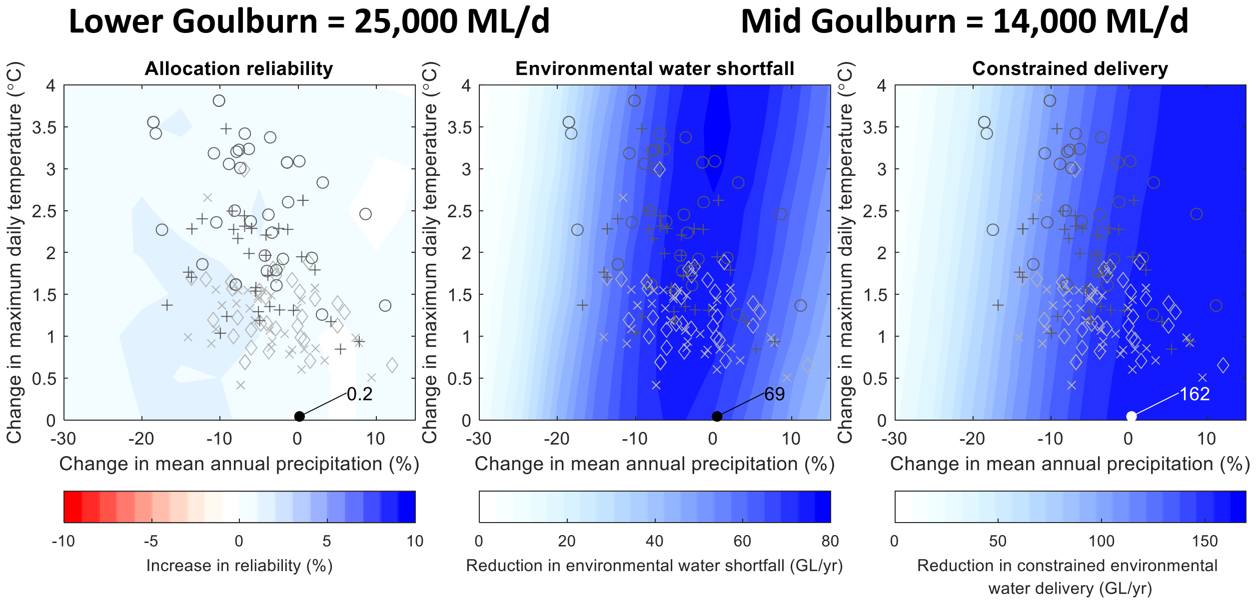


Figure 17. Climate change vulnerability analysis for constraint option of 25,000 ML/d in lower Goulburn and 14,000 ML/d in mid Goulburn. Results are shown relative to the baseline in Figure 13.

6.3. Ecological model results

Additional analysis was undertaken looking at the effectiveness of constraints scenarios in climate adaptation for ecological outcomes. When the calculated stress index is less than -0.5, this represents the point at which the impacts of climate change on ecological outcomes exceed the influence of natural climate variability (and that the outcomes are worse than the baseline, refer to Figure 2 above). This is a potentially significant point and can suggest a decline in population or condition of the ecological endpoint.

This analysis tested how effective the constraint options were at preventing ecological models from reaching this critical stress threshold. The outcomes are shown in Figure 18 for each constraint option. The colours in these panels represent the number of models that leave (blue) or enter (red) the critical stress index of less than -0.5, relative to baseline conditions (current constraints). This is labelled a “tolerability range” for illustrative purposes. Blue regions indicate where there are potentially significant climate adaptation benefits, and red regions indicate potentially increased risk of poor outcomes.

From Figure 18 a), relaxing constraints to 17,000 ML/d in the lower Goulburn provides limited climate adaptation benefits overall according to ecological model outputs. The minor adaptation benefits in moderately drier climates are offset by increased risks in wetter climates.

Although the second option (Figure 18 b)) provides some additional benefits over the first option, more significant benefits projected in the higher two options. Relaxing constraints to 21,000 ML/d in the lower Goulburn and 12,000 ML/d in the mid Goulburn (Figure 18 c)) provides significant climate adaptation benefits in drier climates. This response is strongest for moderately dry climates between 5% to 15% reductions in precipitation. Figure 18 d) shows a stronger adaptation result still, particularly in the moderately dry region of 5% to 15% reductions in precipitation. This region coincides with a large portion of the changes projected by climate models towards 2065 for emissions scenarios SSP2-4.5 and SSP5-8.5.

The most significant climate change adaptation benefits were seen in the highest two constraint options. This suggests that delivering overbank flows in excess of 20,000 ML/d provides important adaptation benefits, and that effective delivery of these flow thresholds is supported by moderate constraints relation in the mid Goulburn.

Common to all options were potentially negative outcomes for some models in wetter climates. This is driven by those models that respond poorly to increased flows, such as bank stability, littoral vegetation, and turtles. Although the current Goulburn Operating Plan seeks to minimise ecological degradation from regulated flow management, these results suggest there may be further refinements that are necessary in sustained periods of wetter conditions.

However, there is a degree of plausible climate change (generally >15% reductions in annual precipitation) beyond which constraints relaxation does not offer adaptation benefits. From Figure 13, this degree of change caused large reductions in reliability and increases in environmental water shortfalls. Notwithstanding constraint issues, the resulting substantial reductions in overall water availability under these harsher climate changes will present significant risks to ecological outcomes in the Goulburn River.

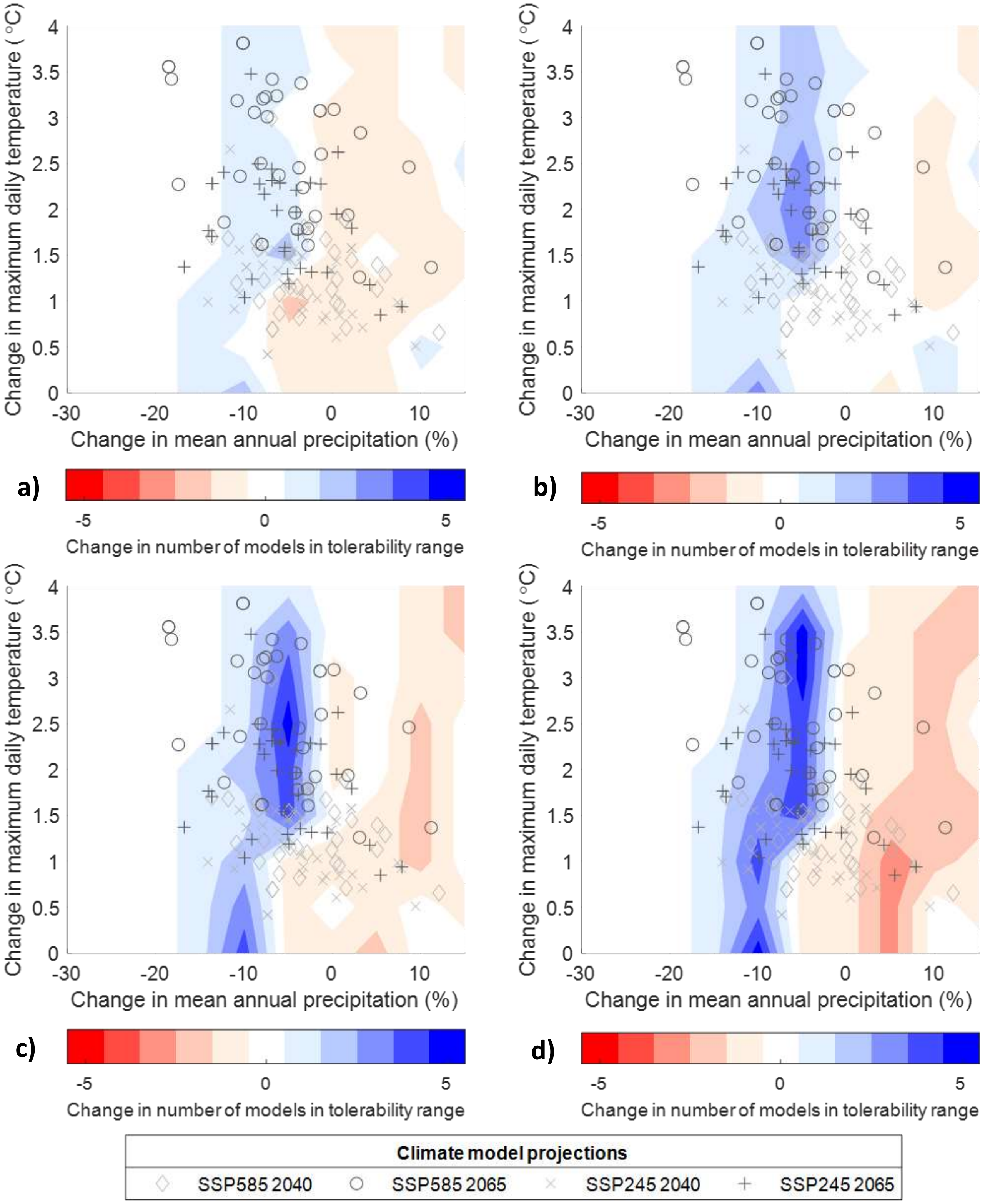


Figure 18. Climate adaptation benefits for ecological models for: a) 17,000 ML/d lower Goulburn and 10,000 ML/d mid Goulburn; b) 21,000 ML/d lower Goulburn and 10,000 ML/d mid Goulburn; c) 21,000 ML/d lower Goulburn and 12,000 ML/d mid Goulburn; and d) 25,000 ML/d lower Goulburn and 14,000 ML/d mid Goulburn. All results are given relative to the baseline (current constraints) scenario.

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Appendix 1 – Disaggregation algorithm updates

The SGEFM was updated to provide temporally correlated daily outputs at multiple locations along the Goulburn River, and to improve the representation of environmental flow freshes.

The new daily output locations include:

- Trawool
- Murchison
- Shepparton; and
- McCoys Bridge

Disaggregated daily outputs can be provided where there is a local gauging station to inform daily flow pattern selection. Flows are temporally correlated between the multiple locations by selecting a “master pattern” based on estimated catchment wetness aggregated across the Goulburn River basin (following the same method as John et al. (2021b)). This master pattern controls the particular sample from which all locations are drawn, thereby preserving flow routing considerations between locations. This method was capable of preserving the relationship between locations (see example in **Error! Reference source not found.**). Since the disaggregation method is stochastic, the intent is not to match the exact observed values (i.e. reproduce the exact sequence of historic daily flows), but to preserve the relationship between the locations – evidenced by the clustering and spread of points around the 1:1 line in **Error! Reference source not found.**.

The disaggregation procedure for environmental flow releases and IVT pulses was also updated. Previously all environmental flow patterns were disaggregated assuming they follow unregulated patterns, and IVTs were disaggregated uniformly. The procedure for disaggregating IVT pulses is outlined in Appendix 1 - IVT modelling and updates in the SGEFM, but follows the example hydrographs provided in the *Operating Rules for the Lower Goulburn River* (Department of Environment Land Water and Planning, 2021b). Environmental flow patterns were revised to use custom disaggregation based on the flow recommendations for freshes. **Error! Reference source not found.** shows example hydrographs for environmental freshes consistent with Horne et al. (2020), and the daily flow pattern used to disaggregate the monthly component of environmental water fresh releases. Baseflows are disaggregated uniformly throughout the month.

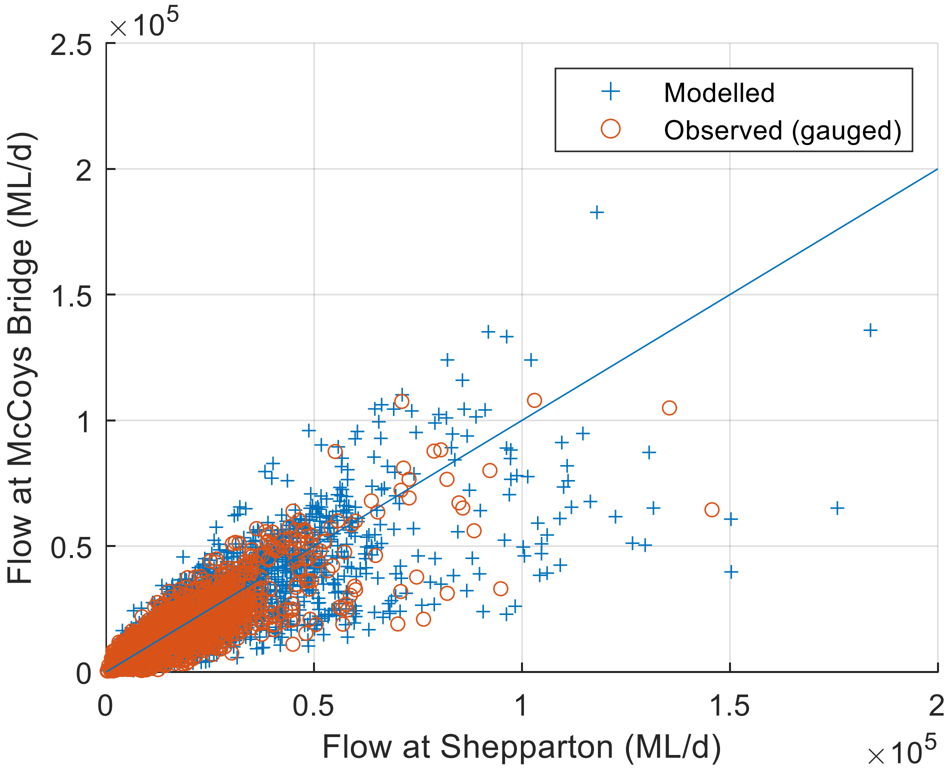

Figure 19. Modelled vs. observed daily flows at Shepparton and McCoys Bridge. The disaggregation method preserves the relationship between flows at both locations as seen in observed flow data.

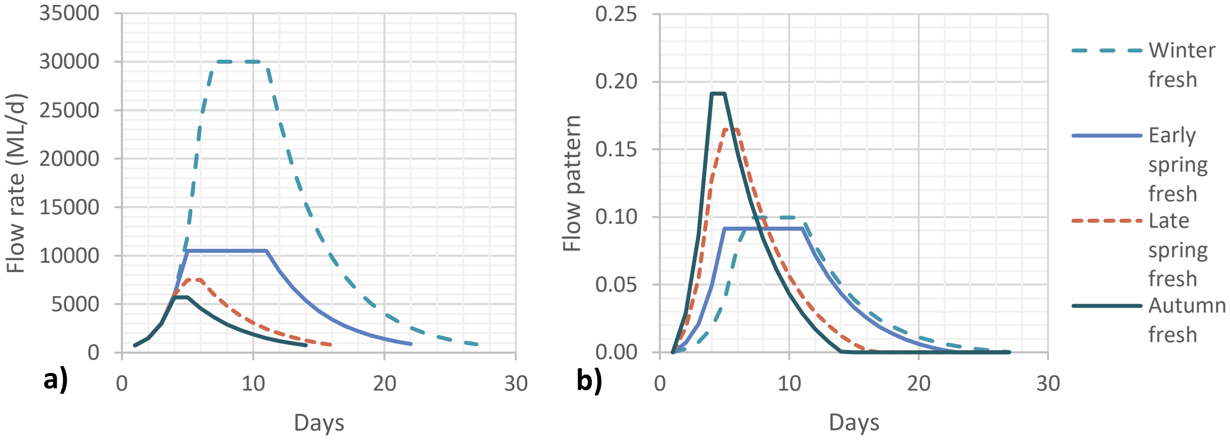

Figure 20. a) Example hydrographs for environmental freshes based on Kaiela flow recommendations; b) daily pattern (proportion of target flow) used for disaggregation of environmental freshes.

Appendix 2 - IVT modelling and updates in the SGEFM

IVT simulations and rules within the SGEFM have been updated with new data and to better represent the new trade and Goulburn operating rules

Since approximately 2012 the volume of water leaving the Goulburn River system as an IVT (inter-valley trade, which is water that is transferred for use by entitlement holders in the Murray system) has substantially increased (Fig 1a). This has resulted in changes to the hydrologic regime along the river (Fig 1b), with an emphasis on higher flow over the summer period. Consequently, this led to environmental degradation along the lower Goulburn River. High unseasonal flows submerged riparian vegetation and prevented new recruitment, reduced habitat for macroinvertebrates and native fish, and contributed to bank erosion.

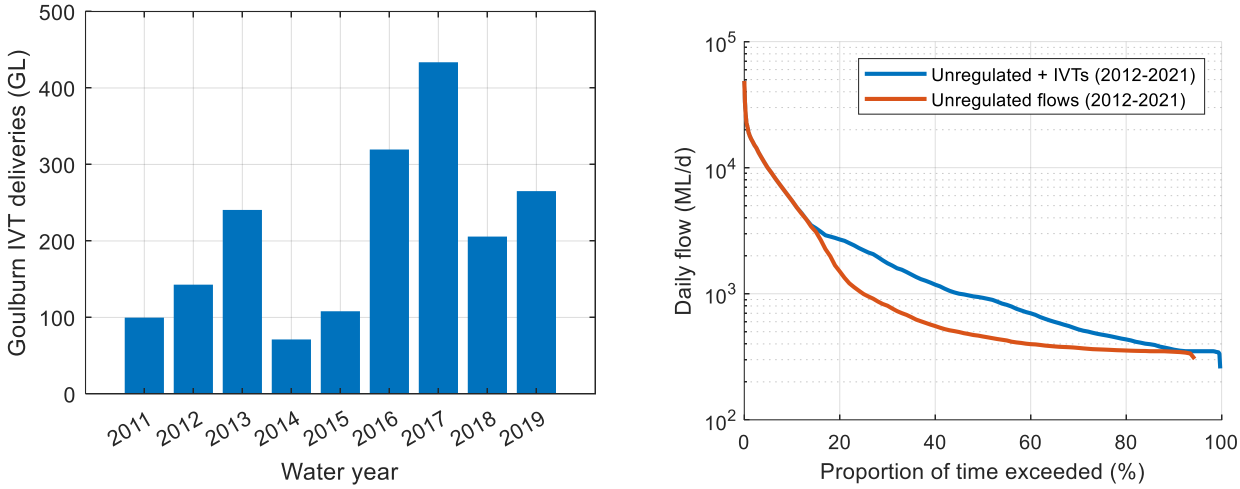

Figure 21. a) Growth of annual IVT volumes in the Goulburn system. b) flow duration curve at McCoys Bridge showing unregulated flows, and the effect of additional IVT water for the period 2012 to 2021. Note that environmental flow releases have been removed from this data.

The University of Melbourne's SGEFM previously modelled annual and monthly IVT deliveries using a simplified scheme based purely on historic data from 2012-2018. Whilst this broadly captured the pattern of annual IVT variations and historic delivery patterns, it was based on a limited dataset and a river operating environment which has substantially changed since 2018.

Trade rule review and outcomes

In 2019, the Victorian Government introduced interim operating rules to prevent further damage and undertook to understand the impacts of different IVT delivery scenarios. From 1 July 2021, the new interim trade rule came into effect. The revised rule is designed to reduce further environmental degradation in the Goulburn River from IVTs and includes a new two-part rule. From 1 July to 15 December, trade is possible when the balance of the Goulburn IVT account (i.e. water owed to the Murray from the Goulburn) is less than 190 GL. From 15 December, further trade is capped over the summer autumn period at 190 GL. This is to ensure the IVT account can be drawn down in time for the next irrigation season, following the revised 2021 operating plan for Goulburn IVTs.

The *Operating Rules for the Lower Goulburn River* (Department of Environment Land Water and Planning, 2021b) describe new limits on the amount of water that can be transferred as IVTs. These are broadly summarised as follows:

- Maximum monthly baseflow targets:
    - 1 July to 31 October: average monthly flow of 1,300 ML/day
    - 1 November to 30 June: average monthly flow of 1,100 ML/day
- Flow pulses to enhance delivery over summer months, but avoid sustained high flows:

  - Up to three pulses of 3,000 ML/d can be made over the summer period. The maximum flow rate of 3,000 ML/d reflects current constraints to protect in-channel private pump infrastructure.
  - The first pulse must follow a period of average regulated releases of no more than 1,100 ML/d for six weeks
  - The second pulse may commence when average regulated flows are no more than 1,100 ML/d for four weeks
  - The third pulse may commence when average regulated flows are no more than 1,100 ML/d for five weeks.

Although these new 2021 rules are still only designated as interim, they provide the most up to date set of procedures to base IVT modelling on. The *Operating Plan for the delivery of water from the Goulburn IVT Account* (Department of Environment Land Water and Planning, 2021a), which is based on the operating rules, describes a "default delivery pattern" which is the expected monthly delivery pattern under average water availability conditions. This assumes 273 GL of IVTs can be delivered in a typical year, including approximately 140 GL of legacy commitments, 50 GL of trade opportunity at the start of the year, and 83 GL progressively throughout the year as additional trade opportunities become available.

SGEFM IVT modelling

Annual and monthly IVT patterns

IVT modelling in the SGEFM has been updated with new data and the revised Goulburn River operating plans. The overall modelling framework of first estimating annual IVT volumes and then simulating monthly patterns has been retained but has been enhanced with new data. One key challenge in precisely predicting IVT volumes, even at an annual timescale, is being able to estimate the differential in price between Goulburn and Murray water allocations, which affects the demands for Goulburn water in the Murray system. This challenge would be common to any water resource model of the Goulburn River system, unless the geographical scope covers much of the southern connected Murray-Darling Basin.

Previously, annual variations around a stationary (de-trended) estimate of long-term annual IVT deliveries was found to be correlated with overall water availability in the Goulburn system towards the start of the irrigation season. In this case, "water availability" is defined as the sum of total allocations and carryover volume at the start of August. This relationship was strengthened with two years of additional data (Figure 22). The exception to this appears to be the 2017 water year which featured high IVT deliveries despite somewhat moderate water availability. However, this year was generally the peak of IVT deliveries and the last year before intervention so may represent an outlier in the data. Although removing the 2017 water year yields a much stronger statistical linear relationship (R^2 value of 0.83 compared to 0.27), it was decided to not exclude it as this risks a spurious degree of confidence in a relationship derived from only a few years of data in a non-stationary operating environment.

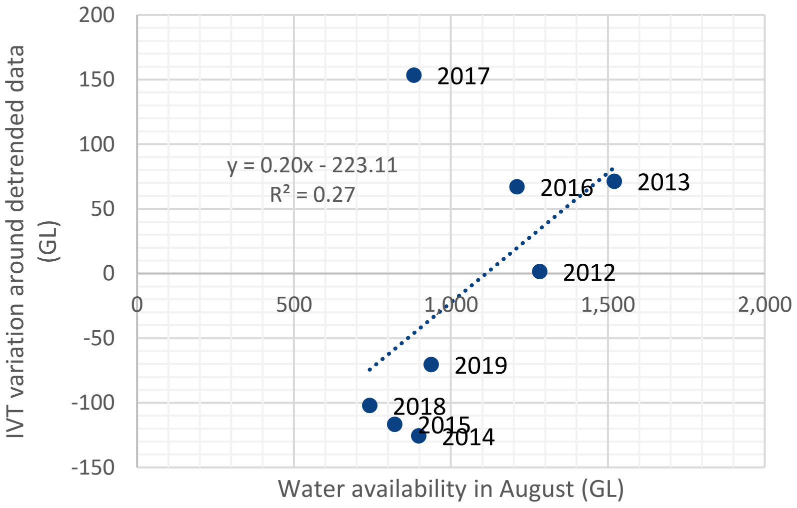

Figure 22. Relationship between available water (carryover plus allocation at the start of August) and detrended annual IVT volumes. This is used to vary annual IVT volumes from the default 273 GL in the SGEFM. Year labels are water years beginning in July.

This relationship is used to vary annual IVTs around the 273 GL default delivery pattern specified by GMW, given this figure is provided for typical water availability conditions. However, even if the total annual delivery is large, the maximum that can be held in the modelled Goulburn IVT account is 190 GL in line with the revised two-part trade rule. Thus, total annual deliveries of greater than 190 GL can be made, but only if suitable volumes are delivered in the September to December period.

The default monthly delivery pattern (Figure 23) is used for annual planning of IVT delivery subject to river operating rules and constraints within the model. The Goulburn River operating plan sets out some examples of primary conditions for varying IVT deliveries from the default pattern. This logic forms the basis of changes to the monthly delivery patterns if the annual IVT volume is different from the default 273 GL.

Figure 23. IVT default delivery pattern from the *Operating Plan for the delivery of water from the Goulburn IVT Account.*

For increased IVTs, the plan suggests deliveries in October to November could be increased by 20 GL (within the operating rules). There are no other examples provided for managing increased IVTs, the maximum IVT in the SGEFM is restricted to 293 GL. For reduced IVTs, the delivery pattern changes by:

1. Decreases are first made by reducing the peak of the summer third pulse to zero
2. Further decreases are managed by reducing deliveries in the September to December period (but not including the December flow pulse)
3. Further decreases still are managed by reducing the peaks of the remaining two summer pulses
4. Finally, any remaining deliveries over the summer period are reduced to zero

These steps have been informed by the variations described for the delivery reduction scenarios in the Goulburn River operating plan. The last two steps only occur in years of very low water availability, where high reliability water shares are unlikely to reach full allocation in the season.

Daily IVT patterns

The SGEFM uses a disaggregation algorithm to produce daily flow estimates from monthly volumes. Previously, monthly IVTs were disaggregated uniformly, but this does not take account of the summer pulse deliveries in the revised operating rules. The disaggregation method has been modified to appropriately model summer pulses. For IVT releases:

- In the September to December period IVTs are delivered uniformly (uniform daily pattern)

- Coinciding with up to three planned pulse deliveries, uniform daily patterns are replaced with custom daily patterns reflecting the example hydrographs provided in the *Operating Rules for the Lower Goulburn River* (Department of Environment Land Water and Planning, 2021b), (Figure 24).

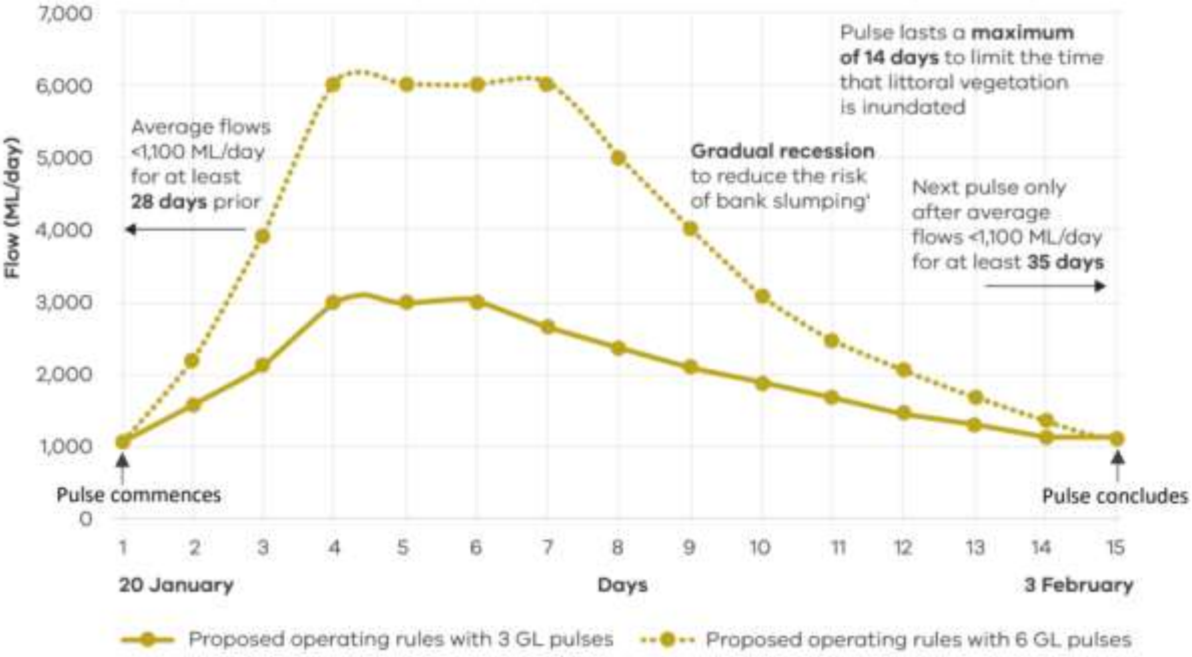

Figure 24. Example hydrograph of summer flow pulse from the *Operating Rules for the Lower Goulburn River*. Note that this also includes an example of a 6,000 ML/d pulse, but this is not used in the SGEFM.

Appendix 3 - Tributary harvesting to Waranga Basin in the SGEFM

Default tributary harvesting mimics existing practices. Functionality has been added to cease harvesting to deliver high flow events to the lower Goulburn River.

Tributary harvesting (the diversion of tributary inflows between Lake Eildon and Goulburn Weir to Waranga Basin) is a normal practice undertaken by GMW to improve seasonal allocation determinations. As per the Bulk Entitlement (Eildon – Goulburn Weir), GMW is entitled to divert tributary inflows to Goulburn Weir to meet demands on the East Goulburn Main Channel, Stuart Murray and Cattanach Canals, and to fill Waranga Basin.

Tributary harvesting normally occurs at the start of the irrigation season when Waranga Basin storage is low, demands along the Stuart Murray and Cattanach Canals is low, and tributary inflows are high. Towards the end of the irrigation season Waranga Basin is drawn down to provide more storage space for winter and spring tributary harvesting.

Tributary inflows are also used to meet any of the Goulburn system demands, which includes private diverters, IVTs and environmental demands in the lower Goulburn. However, when the inflows at Goulburn Weir exceed the capacity to divert water (or the requisite demands) along the Stuart Murray and Cattanach Canals and the Eastern Goulburn Main Channel, this additional water is released downstream. This portion of the flow is not considered as environmental or IVT delivery, (since it is considered as what would have occurred without any environmental or IVT order) as per the Goulburn environmental accounting procedure.

Tributary harvesting in the SGEFM

Tributary harvesting is used to supply extra water to Waranga Basin (in addition to any required transfers from Lake Eildon) up to the maximum operating level of 430 GL from June to November. Note this ramps up from 370 GL in June. The SGEFM reflects decisions to stop harvesting tributary inflows to draw down Waranga storage levels at the end of the irrigation season. From December to February, Waranga Basin is held at an interim operating level of 200 GL. During this time, tributary flows are still diverted to meet Rodney and Waranga demands but are not used to fill Waranga up to full supply or maximum operating level. In addition, in March, the minimum storage is dawn down to 175 GL, and in April and May, to 150 GL, coinciding with GMW practice to maximise airspace for harvesting in the following season. This generally means irrigation demands are more often supplied from stored water in Waranga Basin during these times. These quantities are shown in Figure 25.

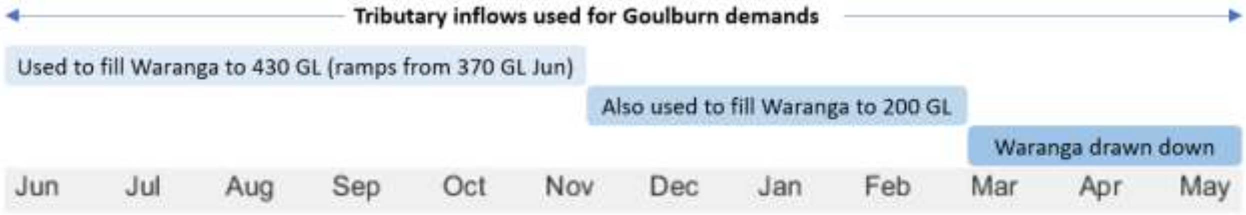

Figure 25. Seasonal use of tributary harvesting in the SGEFM. Note that from December to April, transfers of water from Lake Eildon are used to meet demands and fill Waranga Basin to minimum operating levels.

Tributary harvesting and constraints management

Releases from Lake Eildon alone will likely not be able to take advantage of constraint relaxation in the lower Goulburn River to deliver higher flows. This is because of additional constraints in the reaches below Lake Eildon which limit regulated releases to approximately 9,500 ML/day. The highest environmental flow demands in the lower Goulburn River are from overbank flows which are generally desired in the winter/spring period. This coincides with the normal period of tributary harvesting to Waranga Basin. Thus, some modifications to tributary harvesting would support the delivery of higher flows in the lower Goulburn River where there is a planned high environmental flow release.

The SGEFM includes such an option to modify harvesting behaviour. Toggling this option reduces tributary harvesting when a planned winter/spring fresh or overbank flow is sought. Essentially, normal tributary harvesting volumes are reduced by the volume of the environmental demand (taking into account additional tributary inflows below Goulburn Weir and any IVTs). This can only occur during the specified range of months for the winter fresh as per the latest flow recommendations for the lower Goulburn River (Horne et al., 2020). This behaviour is summarised in Figure 26.

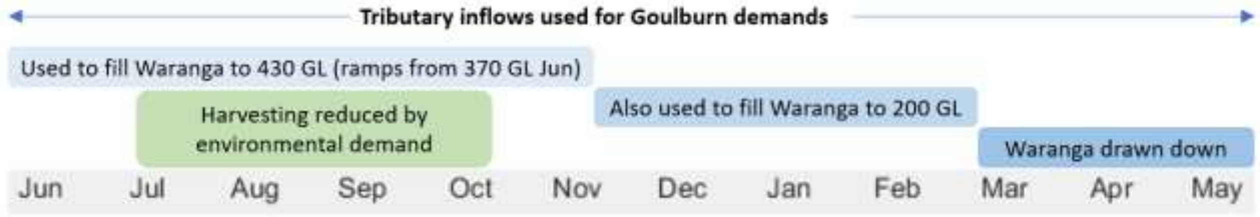

Figure 26. Optional behaviour to cease tributary harvesting to deliver high environmental flows. This option is only triggered by a decision to release a winter fresh/overbank flow (or portion thereof). Regulated releases at Goulburn Weir are still subject to constraint thresholds in this arrangement.

In some years this would mean there was less water harvested by Waranga Basin and more water will need to be released from Eildon to supply Goulburn system water entitlements. However, any impacts on water reliability (which will be further explored in subsequent analysis) are expected to be mitigated by the following factors:

- Passed flows will be debited from environmental accounts, thus stored allocated environmental water will be used to make up any shortfall;
- Waranga harvesting is only reduced if there is sufficient water in the environmental allocations to make up possible shortfalls;
- Foregone tributary harvesting will not allow Waranga Basin to fall below minimum operating levels to ensure maximum delivery capacity at Waranga Basin outlet (180 GL). Note that larger transfers of water from Lake Eildon to Waranga Basin may be required to keep Waranga Basin above minimum operating levels, assuming there is sufficient capacity in the Goulburn River downstream of Lake Eildon to transfer water.

Appendix 4 - Murray demands scenario for Goulburn constraints modelling

The range finding exercise for the Goulburn River in stage 1A of the constraints measures program includes an alternate Murray demands scenario to test the robustness of modelling outcomes

The University of Melbourne's SGEFM model is being used in a "range finding" exercise to explore, at a high level, ecological benefits of a large number of constraints relaxation and future climate scenarios. This model covers the geographical scope of the connected Goulburn, Broken, Campaspe and Loddon rivers, down to their confluence with the Murray River. By default, the model assumes all environmental water entitlements in the Goulburn system are managed to meet Goulburn environmental demands. However, a large volume of the total entitlement is owned by the CEWO, who delegate the management of this water to the VEWH. The VEWH manage all environmental water under a "do no harm" policy in the Goulburn River but do consider Murray benefits in their seasonal watering plans.

The purpose of defining an extra scenario to represent Murray environmental demands is to test the robustness of constraints relaxation recommendations in the Goulburn River. By modifying environmental water management, there may be differences in the nature of modelling outputs and recommendations, even if there is no negative effect on ecological outcomes. Thus, the components of this scenario have been selected to represent a plausible "upper bound" on changes to the Goulburn River flow regime based on alterations for Murray River benefits, whilst still operating in a manner consistent with established management rules.

It is important to note that this does not necessarily represent future policy and is not a recommendation for any changes in environmental water management in the Goulburn River.

The proposed Murray demands scenario was identified with input from GBCMA, VEWH and CEWO. It consists of the following three deviations from default environmental water management:

1. Increased summer flows (IVTs and environmental water)
2. Increased delivery environmental water in spring
3. Reduced carryover opportunities to provide winter overbank flows

These components are summarised in Table 3 and further described below.

Table 3. Proposed modifications for the Murray demands scenario.

Theme	Rationale	Proposed modelling changes
Higher summer flows	High summer IVT deliveries and summer/autumn freshes can be used to provide increased flows to the Murray River. This may also change carryover availability and potential constraint issues in the mid-Goulburn during the summer period.	Modify IVT relationships to always include three pulses of 3,000 ML/d in summer (assuming sufficient modelled IVT demand). By default, the third summer pulse is removed if there is any reduction in modelled IVT demand. The priority of the summer/autumn fresh flow component is increased to be the highest priority behind year-round baseflows and overbank flow. Note this option remains within the requirements of the Goulburn River Operating Plan
Higher spring flows	Larger volumes of environmental water can be used in spring to slow recession in Murray hydrographs and help meet some demands at the South Australian border	Increase the winter/spring variable baseflow component to a target average flow rate of 1,500 ML/d. If a second spring fresh is provided extend the duration at maximum flow from two to six days
Reduced opportunity to carryover environmental water	Lower volumes of carryover water may reduce the feasibility of delivering overbank flows in winter/spring under relaxed constraints	This theme is realised as a consequence of implementing the previous two

Increased summer flows

This represents an increased desire to transfer water from the Goulburn River to the Murray River over the summer/autumn period. It can be modelled by increasing the priority of the autumn fresh flow component and always attempting to deliver the maximum possible summer IVT of 190 GL using three summer pulses of 3,000 ML/d.

By default, the autumn fresh flow component is generally of lower priority depending on water management scenario. This option increases the priority to just below the winter fresh (overbank) and year-round baseflow components (see Table 4 for updated relative priorities for the Murray scenario). Additionally, if lower IVT demands are predicted within the model, reductions are first managed by removing the third summer pulse. This option retains the third summer pulse and preferentially reduces deliveries in the September to December period. If modelled summer IVTs are less than 190 GL, then the third pulse will be reduced as normal. Note this option remains within the requirements of the Goulburn River Operating Plan (Department of Environment, Land, Water and Planning, 2021).

Table 4. Relative priority of flow components based on environmental water management scenario under the Murray scenario based on Horne et al. (2020). Note this is relevant to the Murray scenario only.

	Scenario (brackets show relative priority)				
Flow component	**Drought**	**Dry**	**Below average**	**Average**	**Wet**
Winter fresh (overbank)	1 (2)	1 (2)	1 (2)	1 (2)	1 (2)
Year-round baseflow	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
Winter/spring variable baseflow	1 (4)	1 (4)	1 (5)	1 (6)	1 (6)
Early spring fresh	3 (3)	2 (3)	1 (4)	1 (4)	1 (4)
Recession management	3 (5)	3 (7)	1 (6)	1 (8)	1 (7)
Winter fresh in following year[1]	0	3 (6)	2 (7)	1 (7)	2 (8)
Autumn fresh	0	0	4 (3)	3 (3)	1 (3)
Late spring fresh	0	3 (5)	3 (8)	1 (5)	1 (5)

Note: 1 = priority, full delivery, 2 = priority, partial delivery, 3 = opportunity, full delivery, 4 = opportunity, partial delivery, 0 = do not deliver. A "partial delivery" assumes 75% of the total flow volume compared to a "full delivery." Priority components are first met, with opportunistic components met assuming available water.

[1] This is provided in the first month of the following water year (July). It has the same volume, duration and frequency as the early spring fresh flow component.

Increased delivery of environmental water in spring

Increases in environmental water use in the Goulburn River in spring can be used to help provide some Murray system benefits. Goulburn inflows can help to reduce recession (or "fill in" hydrographs) of Murray flows. If they are provided early enough in the season, they can also help meet demands near the South Australian border.

This option seeks to maximise environmental water use in winter/spring in the Goulburn River. Higher flows are delivered to the Murray River in two ways. Firstly, by extending the duration of any second spring fresh from two to six days. This can increase the total volume of environmental water in this event by up to 30 GL, assuming a target flow rate of 7,500 ML/d. Secondly, the winter/spring variable baseflow component is increased closer to "natural" baseflow conditions. The flow recommendations specify a minimum of 500 ML/d up to "natural" conditions, by passing natural tributary inflows. This option increases the average target baseflow to 1500 ML/d over this period, a lower figure so it is viable in most years to pass tributary flow without Eildon releases. As variability is key to this flow component, it is based on naturally occurring trigger flows of 2,500 ML/day at Seymour.

Reduced carryover opportunities to provide winter overbank flows

This option follows as consequence of modelling the first two changes rather than requiring any separate modelling. Higher environmental flow deliveries in winter/spring and summer/autumn from the first two changes may decrease carryover volumes at the end of the season. Sufficient volumes of carryover environmental water are important to be able to deliver overbank flows under relaxed constraints. This is especially relevant during earlier seasonal opportunities in the late winter/spring period where seasonal allocation determinations may be low. The delivery of larger environmental flows will generally follow an opportunistic approach based on sufficient tributary inflows above and below Goulburn Weir, thus there may not be time to allow within-year allocations to provide the full balance to meet environmental demands. The previous two options seek to maximise environmental water delivery throughout the year, thus reduce the opportunity for larger volumes of carryover water to be available.