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Modelling the Murray–Darling Basin Southern Connected System

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Abstract: The Southern Connected System (SCS) is located within the Murray–Darling Basin, Australia. It comprises the Snowy Mountains Hydro-electric Scheme, the Murrumbidgee river system, and the Murray–Darling Basin river system. These systems are described by four river system models: the Snowy Hydro Scheme, Upper Murrumbidgee, regulated Murrumbidgee and the Lower-Darling and Murray. However, more broadly many other upstream river system models contribute flow and allocation information. These include the NSW Barwon-Darling model, and Victoria Kiewa, Ovens, and Goulburn-Broken-Campaspe-Coliban-Loddon models. Noting that the Barwon-Darling model receives contributions from 10 upstream river system models, including contributions from 5 Queensland river system models (Figure 1).

Previously the SCS models were largely run independently with inputs from upstream models as fixed inputs for a range of development scenarios. However, there are a range of feedbacks between these models that are sufficiently large enough that they need to be considered. The SCS modelling suite considers the connections and feedbacks via an iterative approach. This is the first time that these feedbacks have been considered.

This paper describes the physical and management connections between the models that describe the SCS. It details the feedbacks between the models and how this was managed within the modelling framework. It provides insights into the relative importance of the different variables and the importance of considering these within the broader modelling process of downstream systems. The results demonstrate the significance of modelling feedbacks through iterations and the need to be considered in future modelling of the SCS.

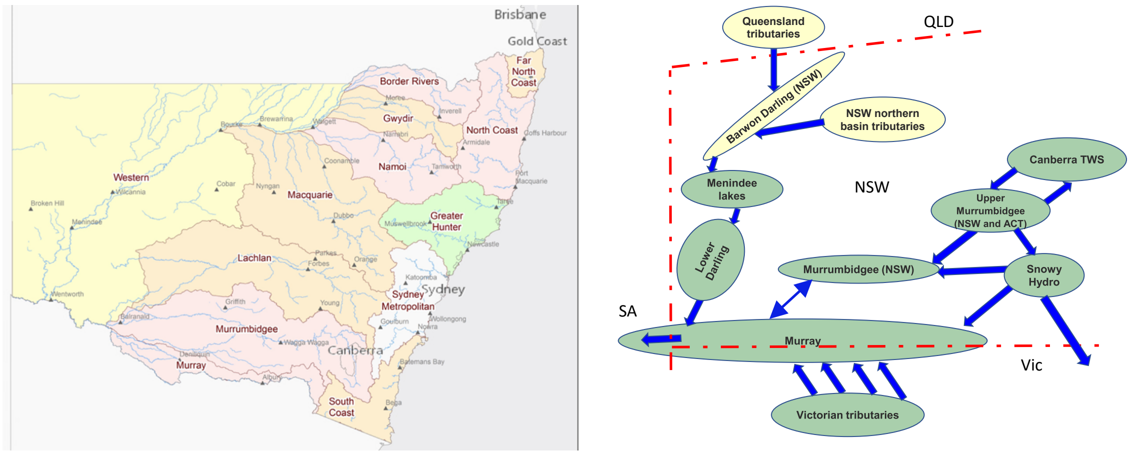

Figure 1. NSW regional water strategy regions and modelling components in the Southern Connected System (green colour)

Keywords: *Murray River, Murrumbidgee River, Snowy Mountains Hydro-electric Scheme, river systems*

1. INTRODUCTION

The NSW Department of Planning and Environment is preparing 12 new regional water strategies (RWS) to plan and manage the water needs in each NSW region over the next 20-40 years (Figure 1). These strategies bring together the best and latest climate evidence with a wide range of tools and solutions (DPIE, 2020a). The RWS is supported by a range of river system models that simulate the physical and management processes of river and water supply systems over 100 years. This paper describes the process of building the Southern Connected System river system modelling suite to support the Murrumbidgee, Murray, and Western Regional Water Strategies.

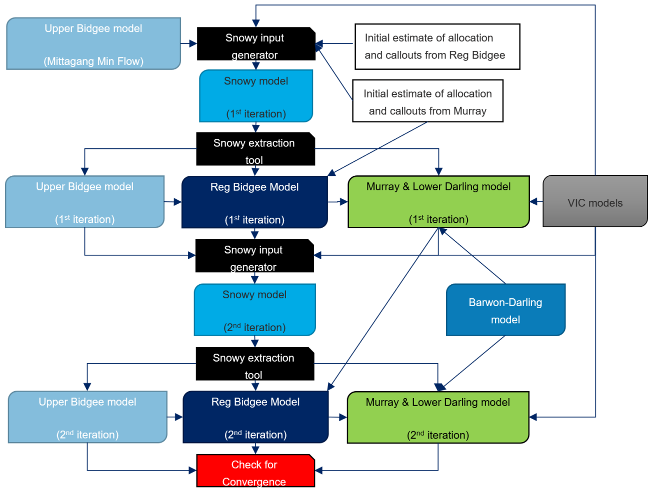

Figure 2. Flow of information between river system models for each iteration

The Southern Connected System (SCS) is located within the Murray–Darling Basin, Australia. It comprises the Snowy Mountains hydro-electric scheme, the Murrumbidgee river system, and the Murray–Darling Basin river system. These systems are described by four river system models; the Snowy Hydro Scheme (SHSM), Upper Murrumbidgee (UM), regulated Murrumbidgee (BM) and the Lower-Darling and Murray (SMM). However, more broadly many other upstream river system models contribute flow and allocation information. These include the NSW Barwon-Darling model, and Victoria Kiewa, Ovens, and Goulburn-Broken-Campaspe-Coliban-Loddon (GBCL) models. Noting that the Barwon-Darling model receives contributions from 10 upstream river system models, including contributions from 5 Queensland river system models (Figure 1).

The RWS applies a consistent approach to three climate scenarios throughout the Murray–Basin. These include 132 years of instrumental climate (1890-2022), 10,000 years of stochastic climate data (Leonard et al., 2022) and climate change adjusted stochastic climate (DPIE, 2020b and Olsen et. al, 2016). This climate data is input into consistent runoff generation models. The Sacramento rainfall-runoff model was used everywhere except the Snowy Mountain scheme where snow processes where consider by the modified GR4J rainfall-runoff model (HARC, 2022a). These models provide headwater and residual inputs into the river system models for the different climate scenarios.

Previously the SCS models were largely run independently with inputs from upstream models as fixed inputs for a range of development scenarios. However, there are a range of feedbacks between these models that are sufficiently large enough that they need to be considered. The SCS modelling suite considers the connections and feedbacks via an iterative approach, discussed in detail in Section 2.2. This is the first time that these feedbacks have been considered dynamically.

The following sections describe the interactions and connections between the various models, how feedbacks are considered, provides some results and discussion on the linkages between models and then provides some concluding remarks on the benefits of this approach.

2. BUILDING THE SOUTHERN CONNECTED SYSTEM MODELLING SUITE

2.1. Southern Connected System river system models

The SCS is modelled by a suite of eight models (SHSM, UM, BM, SMM, GBCL, Ovens, Kiewa, and Barwon-Darling models). The models run on a range of modelling platforms (eWater Source (Welsh et al. 2012) and REALM (Perera et al. 2005)) and for different time steps (daily, weekly, and monthly). There are feedbacks between the SHSM, UM, BM, and SMM and this forms the core of the SCS modelling suite. To be able to consider these feedbacks the models are run through multiple iterations until an acceptable convergence is reached. Figure 2 shows the flow of information between the various models for each of the iterations.

SHSM considers nine power stations, 16 major dams, 80 kilometres of aqueducts and 145 km of interconnected tunnels. The model commences in the headwaters of the Murrumbidgee, Goodradigbee, Tumut, Snowy, Tooma and Swampy Plains rivers (HARC, 2022a). The model ends with outflows from Tantangara Reservoir, Goodradigbee flume, Blowering Dam, Tooma Reservoir, Jindabyne Reservoir, Geehi Dam and Middle Creek

Weir and Khancoban Pondage. The model considers the water sharing arrangements described in the Snowy Water Licence (NSW, 2020). The influence of the electricity market driven demand is not explicitly considered.

UM considers the river system upstream of Burrinjuck Dam. It includes Tantangara Dam and the ACT water supply system comprising Googong, Corin, Bendora and Cotter Dams. The model is configured to model the current operational conditions and water sharing plan rules of the Murrumbidgee unregulated system (https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2012-0492). This includes the irrigation, environmental, stock, and domestic and town water supply demands within the unregulated system.

BM commences at the headwaters of Burrinjuck and Blowering Dams. It ends at Billabong Creek at Darlot gauge and at the Murrumbidgee confluence with the Murray River. The model is configured to model the current operational conditions and water sharing plan rules of the Murrumbidgee regulated system (https://legislation.nsw.gov.au/view/html/inforce/current/sl-2016-0367). This includes the irrigation, environmental, stock, and domestic and town water supply demands within the regulated system.

SMM simulates river system behaviour within the Murray River (from Murray headwaters and Khancoban Pondage to the river mouth barrages) and along the Lower Darling River (from Menindee Lakes to Wentworth). The model includes Dartmouth, Hume, Yarrawonga, Menindee Lakes, and Lake Victoria major storages. The model considers the river management rules (MDBA, 2015) and is configured for Basin Development Limit (BDL) conditions (MDBA, 2019). To be able to operate within the framework the model needed to be modified to cope with extreme climate driven conditions, modelled inflows above Hume dam, climate driven town water supply demands, South Australian demands and the Snowy water licence related interactions, these changes are described in Alam et al., 2023.

2.2. Information exchanged between models

There is a range of information that is exchanged between SCS models (Table 1). The Barwon-Darling, Kiewa, Ovens, and GBCL models predominantly provide inflows. The GBCL model also provides allocations for the Goulburn and Campaspe regulated systems. The SHSM, UM, BM and SMM also exchange information from downstream to upstream and are consequently part of a feedback process. The type of information that is exchanged comprises flow, storage volumes, storage spills, water use, environmental release requirements, allocations, various accounts, and call outs.

Table 1. Information exchanged between SCS models

Model output	Model input	Description
Snowy (SHSM)	Upper Murrumbidgee (UM)	Eucumbene volume; Goodradigbee Water Savings Allocation; Murrumbidgee Water Savings Allocation
	Murrumbidgee (BM)	Jounama and Net Jounama releases; Tumut 1 spill; Dry Inflow Sequence Volume (DISV); Required Annual Release (RAR); RAR forecast
	Murray (SMM)	Murray 1 power station release; Tooma and Geehi spills; Middle and Strzelecki Creek releases; DISV; RAR; Flexible pre-release; Unencumbered Above Target Water; Below Target Water; Combined Eucumbene and Jindabyne spills; River Murray Increased Flow reduction; Above Target Water reduction
Upper Murrumbidgee (UM)	Murrumbidgee (BM)	Burrinjuck Dam and residual inflows; Goodradigbee at Wee Jasper
Kiewa	Murray (SMM)	Kiewa at Bandiana
Ovens	Murray (SMM)	Ovens at Peechelba
GBCL	Murray (SMM)	Goulburn at McCoys Bridge; Campaspe at Rochester; Loddon at Appin South; Allocations (HRWS, LRWS)
Murrumbidgee (BM)	Murray (SMM)	Billabong Creek at Darlot; Murrumbidgee at Balranald; Demands below Balranald; Allocations (GS and HS); Murrumbidgee Spill from Burrinjuck
Barwon-Darling	Murray (SMM)	Menindee and Talywalka Creek inflow; Darling at Bourke
Upper Murrumbidgee (UM)	Snowy (SHSM)	Mittagang Crossing orders
Murrumbidgee (BM)	Snowy (SHSM)	Burrinjuck and Blowering volume; Blowering spills and release; Water use; Allocations (GS, HS, MIA, and CIA); Pre-release Compensation Reserve; Drought call out
Murray (SMM)	Snowy (SHSM)	Dartmouth, Hume, Menindee, and Lake Victoria volumes; Hume spills; Water use; Allocations (GS, HS, HRWS, LRWS); RMIF and drought callouts; GS effective allocation
GBCL	Snowy (SHSM)	Allocations (HRWS and LRWS)
Murray (SMM)	Murrumbidgee (BM)	Flow Wakool junction; SA surplus flow; NSW Lake Victoria volume; Murray NSW GS Effective Allocation; Finley Escape flow (fixed pattern)

The SCS runs on a daily time step, however, the SHSM and GBCL run on a monthly time step and the Ovens model on weekly time step. The GBCL monthly outputs are disaggregated to daily based on the daily GBCCL model and the Ovens model outputs are disaggregated using the upstream rainfall runoff model inflows (HARC, 2022b). The Snowy interaction is more complex with inputs to downstream models being converted to daily and feedbacks from downstream daily models converted to monthly. There are Python scripts to create input files for the SHSM, UM, BM and SMM.

2.3. Python scripts for connecting models

The Snowy input script combines climate, runoff, and model outputs to provide a text input file for SHSM. The script also postprocesses downstream model outputs to derive specific Snowy inputs including:

- Montane releases to Snowy, Murrumbidgee, Goodradigbee rivers and Strzelecki and Middle Creeks as well as internal releases within the Snowy system.
- Snowy-Murray (SM) water savings based on Murray and GBCL allocations and respective water savings entitlements.
- Snowy-Tumut (ST) water savings based on Murrumbidgee allocations and water savings entitlements.
- SM relaxation volume and associated call outs based on storage volumes and usage.
- ST relaxation volume and associated call outs based on storage volumes, usage, and Pre-release Compensation Reserve (PCR)(NSW, 2002).
- SM Wet Sequence Protection (WSP) based on associated flex release and Hume unused spills.
- ST WSP based on associated flex release and Blowering unused spills.
- SM Within Year Release Requirement (WYRR) based on SM Required Annual Release (RAR), Snowy-Murray releases, WSP and Hume spills.
- ST WYRR based on ST RAR, Net Jounama releases, WSP and Blowering unused spills.

The Snowy output script combines the results from the SHSM with the results of BM and SMM used as inputs to derive RAR and flexible releases, as well and perform daily disaggregation of the Snowy outputs that are used in the daily models such as UM, BM, SMM. The Murrumbidgee script gathers outputs from the SHSM, UM and SMM. The Murray script gathers outputs from the SHSM and SM. It post processes the monthly GBCL models to daily as well as post processing a column of the total monthly Menindee Lakes inflows for resource assessment.

3. MODELLING FEEDBACKS BETWEEN RIVER SYSTEM MODELS

The orders, allocations and call outs in the UM, BM and SMM models affect the release of the water from the Snowy Mountains Scheme,

Target flows on the Murrumbidgee at Mittagang Crossing generate orders to Tantangara that subject to storage inflows are released from the storage.

Allocations in the Murrumbidgee, Murray and GBCL systems define water savings and consequent environmental releases both internally and downstream of the Snowy Scheme. These are divided into three components: Snowy River Increase flows (SRIF), River Murray Increased Flows (RMIF) and Snowy Montane Increased flow (SMRIF). The RMIF receives a proportion of the water saving and an account of this is maintained. This water is subsequently called out by SMM for environmental purposes. The SRIF receives the remainder of the water savings up to 212 GL and is released based on the pattern of flows in the Snowy River at Paddy's corner (Reinfields et. al, 2013). The SMRIF is based on the SRIF and the amount of power generation that would be forfeited and in combination with an allocation function defines annual releases targets from Tantangara Dam, Goodradigbee flume, and Middle and Strzelecki creek aqueduct intakes.

The relaxation volume (RV) is used to reduce Snowy required releases to Murray and Murrumbidgee systems when there is anticipated full allocation i.e., times when less water is required from Snowy Scheme. The relaxation volume subsequently reduces the respective RAR. A relaxation volume call out of up to 100 GL can be made if there was an RV in the previous year and the current water year allocation is below target. This will increase the RAR in a year.

Spills from Murray and Murrumbidgee systems influence the calculation of Wet Sequence Protection (WSP) and Within Year Release Requirements (WYRR). WSP compensates for flex releases in the previous water year that subsequently spill in the current year. The WYRR ensures a volume of Snowy release from December to end of April and is subject to WSP release and spills. These increase the annual RAR but overall are a redistribution of volume across time and don't have a large influence on long-term results.

The drought and PCR call outs from downstream affect inflows into the downstream models in very dry conditions. However, these are rare and don't have a large influence in long term results.

The flow outputs from SHSM change the amount of resource that is available to share to water users within respective systems downstream systems.

The Murray inputs to the BM control the use of environmental replenishments in the Murrumbidgee system which impacts on the Balranald flows.

The feedbacks are managed by running models multiple times. The starting model is the SHSM. For the first iteration regression-based relationships were used to estimate inputs (Figure 2). Iterations continue until there is convergence in the Snowy flow inputs into the SMM and BM. Convergence is based on average annual inflow differences and exceedance curve matching.

4. RESULTS OF MODEL CONVERGENCE

The following results provide a comparison between key pieces of information that are exchanged between models for iterations 2, 3 and 4 of the feedback modelling process. They show the convergence of this information over successive iterations. Table 2 shows a comparison of the key statistics for releases into the Murray and Murrumbidgee systems from the Snowy Scheme (01/07/1891 – 30/06/2020), the values in brackets represent the percentage change from the previous iteration.

Table 2. Comparison of iteration 2, 3 and 4 inflows into Murray and Murrumbidgee systems

Volume (GL/y)	Mean Iteration 2	Mean Iteration 3	Mean Iteration 4	Median Iteration 2	Median Iteration 3	Median Iteration 4
Murray 1 power station	1,041	995 (-4.4%)	991 (-0.4%)	996	947 (-4.9%)	942 (-0.5%)
Middle and Strzelecki	52	52	52	40	40	40
Net Jounama	967	1,010 (4.4%)	1,018 (0.8%)	933	979 (4.9%)	1,000 (2.1%)
Murray NSW Diversions	1,639	1,588 (-3.1%)	1,596 (0.5%)	1,789	1,749 (-2.2%)	1,759 (0.5%)
Murrumbidgee NSW General Security Diversions	616	626 (1.6%)	628 (0.3%)	650	680 (4.5%)	648 (-4.7%)
Billabong Creek at Darlot (410134) Flow	228	229 (0.5%)	230 (0.2%)	144	146 (1.5%)	146 (-0.1%)
Murrumbidgee at Balranald (410130) Flow	1,218	1,230 (1.0%)	1,238 (0.7%)	827	824 (-0.4%)	839 (1.8%)

The convergence of water savings over the instrumental period ensures that environmental releases in the Snowy Scheme will not change. Figure 3 shows NSW Murray and Murrumbidgee general security allocations between iterations.

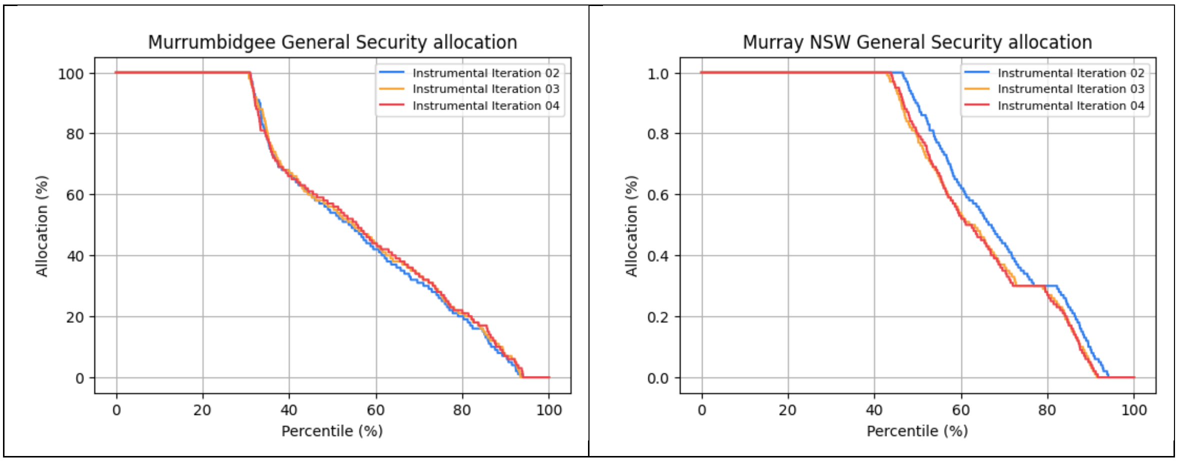

Figure 3. Comparison of exceedance curves Murrumbidgee and Murray General Security allocations

Figure 4 shows the match between Murrumbidgee end of system to Murray at Darlot and Balranald. This shows that the volume of water entering Murray from Murrumbidgee has not changed significantly between iteration 3 and 4.

Figure 5 shows a close match between iteration 3 and 4 of South Australia surplus flows and NSW volume in Lake Victoria. This ensures environmental flow regulation in the Murrumbidgee has converged.

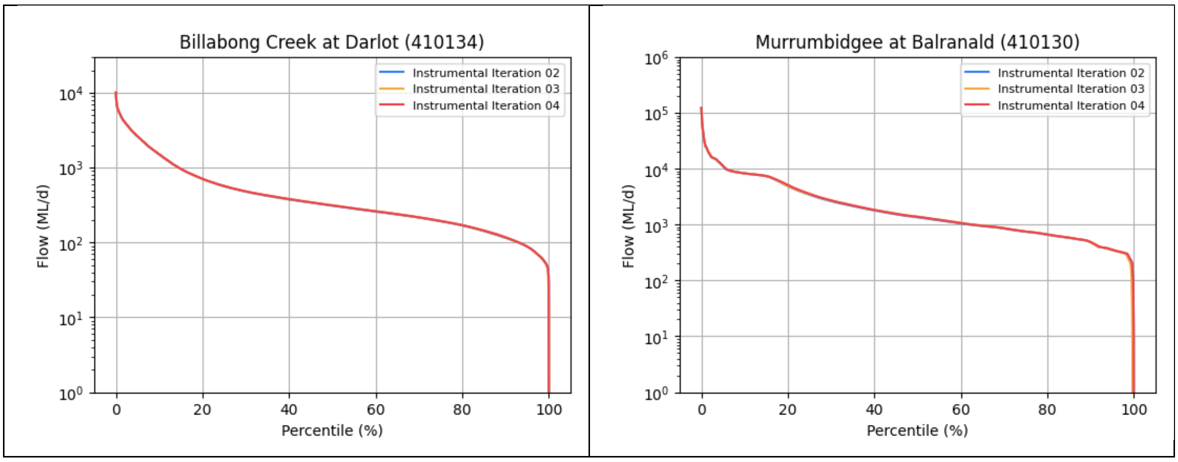

Figure 4. Comparison of exceedance curves for Billabong Ck at Darlot and Murrumbidgee at Balranald

Table 3. Comparison of iteration 2, 3 and 4 outflows from Murrumbidgee Systems at various exceedance percentiles

Volume (GL/y)	Iteration 02 10%	Iteration 03 10%	Iteration 04 10%	Iteration 02 50%	Iteration 03 50%	Iteration 04 50%	Iteration 02 90%	Iteration 03 90%	Iteration 04 90%
Billabong Creek at Darlot	71	73	72	144	146	146	490	490	490
Murrumbidgee at Balranald	330	326	329	827	824	839	2,331	2,340	2,392

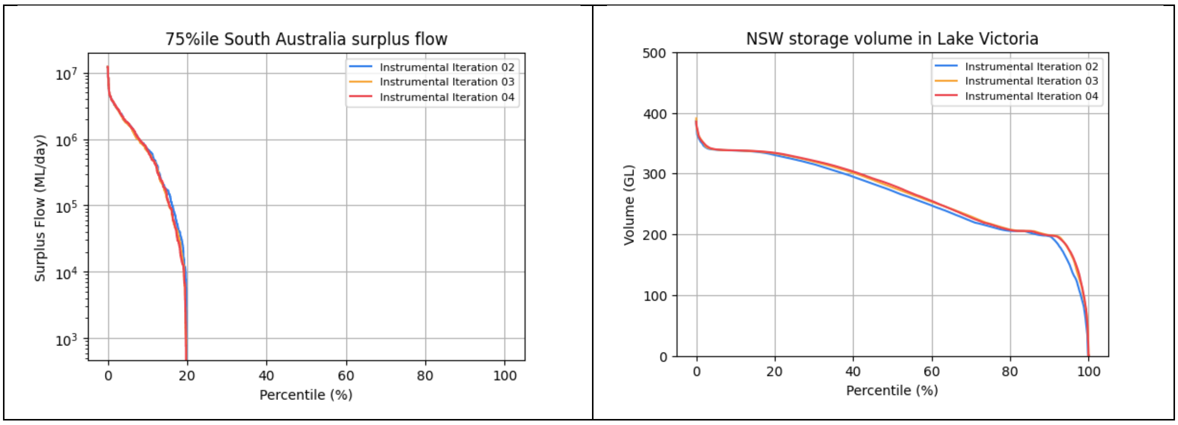

Figure 5. Comparison of South Australia surplus flow and NSW volume in Lake Victoria

It can be seen from the results discussed above that the model has acceptably converged to within 1% of volume by iteration 4.

5. DISCUSSION

Figure 6 shows a time series comparison of successive iterations of Net Jounama release. On average the volumes are similar however this can vary between years. This is predominantly a redistribution of water between years. This is due to the feedback between Snowy releases and allocations in the downstream models. The change in allocations affects the relaxation volume and flex pre-release which in turn impacts the Snowy required release.

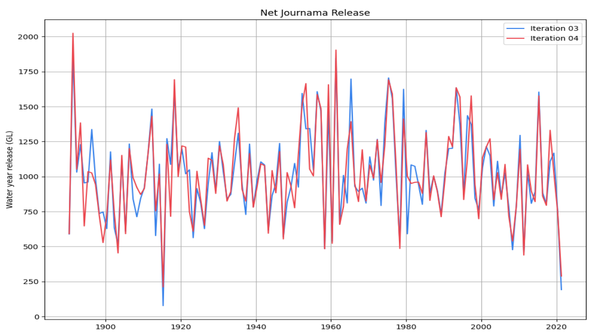

Figure 6. Comparison of net Jounama inflows

A further two iterations have been run and the results oscillate and do not converge. This issue does not create a large problem as Hume and Blowering storages smooth this across time.

Not all interactions between models were considered. Inter-valley Transfers (IVT) between Murrumbidgee and Murray via the Snowy have historically occurred but are difficult to model and it was assumed these do not occur. These transfers can be significant but are based on one-off operational decisions and cannot be modelled.

The influence of the energy market on Snowy releases was not considered as this is difficult to estimate over the long term. This effects the timing of required releases and the amount of above target release. Note the above target water release for additional energy generation was based on a random number. This in turn affects flex pre-release, WSP and WYRR. According to the Snowy Water licence Relaxation Volume calculation is based on 2002 development conditions, however, this study has assumed current development conditions. To consider this would require different model scenarios to be run concurrently which adds further complexity to the iteration process. Future work is exploring the sensitivity of this assumption.

6. CONCLUSION

This is the first time that the feedbacks in the Southern Connected System have been modelled dynamically. This has provided insights into how the systems interact with each other. It has shown the relative sensitivities of the different feedbacks between models. It has shown the frequency of the different types of call outs. It identifies areas where previous assumptions in running standalone models were not correct and how this impacts results. This is has shown the importance of considering these feedbacks in future modelling.

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