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RQ6 – Progress towards enhancing low flow predictions

Report T2.6.4

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Foreword

The Murray–Darling Water and Environment Research Program is an Australian Government initiative to strengthen scientific knowledge of the Murray–Darling Basin. It is designed to help inform water and environment management decisions which will improve outcomes for the Basin and its communities. Four priority themes have been identified as the focus of the strategic research: Climate Adaptation, Hydrology, Environmental Outcomes, and Social, Economic and Cultural Outcomes. Research Question 6 (RQ6) – Enhancing low flow prediction to support water resource planning – is one of the research projects in the Hydrology theme. This report is a summary report describing the progress made in FY22-23 toward better process representation of water exchange between river and groundwater in river systems models.

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Acknowledgments

This work is supported through funding from the Murray–Darling Water and Environment Research Program (MD-WERP). MD-WERP is a $20 million research partnership between the Department of Climate Change, Energy, the Environment and Water (DCCEEW), the Commonwealth Environmental Water Office (CEWO) and the Murray-Darling Basin Authority (MDBA). MD-WERP is an initiative to strengthen scientific knowledge to help inform water and environmental management decisions to improve outcomes for the Basin and its communities.

This work was carried out as part of the Hydrology theme, led by the CSIRO consortia.

Executive summary

The focus of the research in Project RQ6 is to improve the simulation of low flows that are important to maintain environmental/refugia conditions, avoid poor water quality risk and to support downstream water uses. RQ6 aims to develop methods to improve low flow estimation in unregulated and regulated river reaches, to better inform ecological outcomes and water resources management and planning. The focus in 2022/2023 was on developing a river reach scale water exchange function that incorporates river bed and bank storage processes and losses to groundwater dependent upon groundwater levels. These have been identified as key physical processes missing from river system models that are important in the simulation of low flows.

A new algorithm has been developed to incorporate the processes of bed storage and feedback from groundwater levels on river losses. This new algorithm has been coded into the AWRA-R river system model for testing. This new algorithm has been used in the modified AWRA-R model to calibrate the flow in the Border Rivers and Gwydir catchments as a test case. These catchments were chosen as the 2018 and 2019 environmental flow releases provide a controlled test case of low flow conditions that difficult to simulate with current models.

The preliminary results show some improvement in the low flow simulations without negatively impacting the modelling of other parts of the flow hydrograph. The research in 2023/2024 will further develop and test the water exchange function and quantify model improvement in other key reaches in the Murray-Darling Basin.

1 Introduction

The Murray-Darling Basin (MDB) is the most stressed river system in Australia with significant tensions in the sharing of water between competing uses. The Water Sharing Plans at both the state and commonwealth levels are informed by river systems models that simulate flows and the various components of the water balance. Recently the increased emphasis placed on environmental flows (Nicolle et al., 2014, Hallouin et al., 2020) and restrictions on extractions during low flow periods has highlighted the poor model performance in the simulation of low flows (Ivkovic et al., 2014, Ye et al., 1997). These models implicitly assume stationary conditions in simulating river losses as a function of flow without considering the physical processes involved. The findings from the first year of the RQ6 research project showed that losing conditions (losses from the river to groundwater) have become more prevalent in recent decades across the MDB (Crosbie et al., 2023) and that many reaches have decreased in propensity for perennial conditions (Crosbie et al., 2022a). These elements of the river flow regime are not stationary in time and need to be incorporated into the water exchange functions of river system models to provide better simulations of low flows.

A piece wise linear (PWL) loss function is conventionally used in river system models and has been shown to be adequate for modelling the total flow as used in water resource management (Kim et al., 2013). This form of loss function estimates the losses based on the flow and so has no knowledge of antecedent conditions or interactions with groundwater. This one-way coupling of surface water to groundwater results cannot adequately simulate the variable losing conditions and is the main cause of poor simulation of low flows (Jachens et al., 2021).

The objectives of this work are to (i) develop a new loss function or water exchange function for river system models that better represent the physical processes of river losses to enhance low flow predictions; (ii) test the new function to quantify improvements in low flow performance without sacrificing the ability to simulate other parts of the flow hydrograph; and (iii) demonstrate the new water exchange function in a variety of flow regimes throughout the Murray-Darling Basin. This report summarises the research undertaken in FY22/23.

2 Case study catchments

The first year of the project investigated how elements of the flow regime have changed through time in the MDB. These observations identified areas of the MDB where the surface water – groundwater interactions have been changing. There is a trend toward an increase in reaches losing water to groundwater in recent decades, particularly in the northern MDB (Crosbie et al., 2022b, Crosbie et al., 2023). There is also a trend in a reduction in the perenniality of flow, again particularly in the northern MDB (Crosbie et al., 2022a). The ideal test catchments for a new water exchange function would have varying connectivity between surface water and groundwater (Figure 1a) and also be subjected to wetting and drying cycles of intermittent flows (Figure 1b).

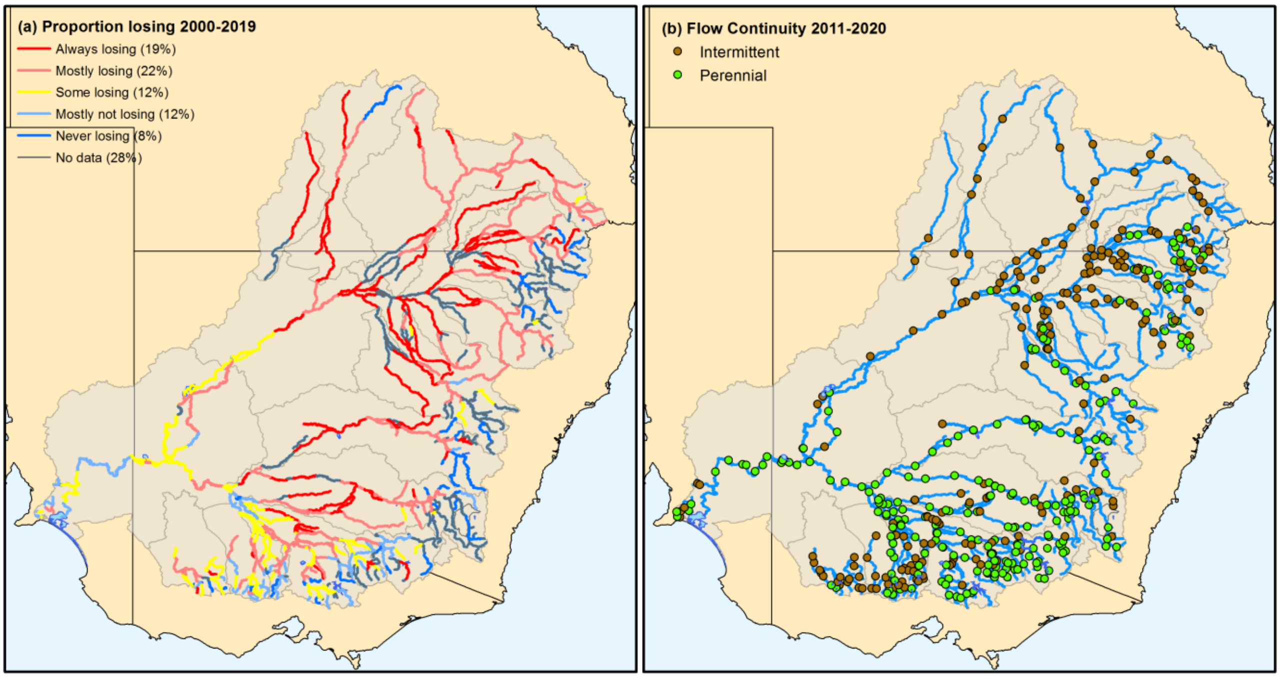

Figure 1 (a) proportion of river reaches experiencing losing conditions over the period 2000 to 2019 (b) average flow continuity over the period 2011 to 2020

The Gwydir and Border Rivers catchments were selected as the case study catchments for testing the new loss function (Figure 2). As well as having the variability of flow needed for testing, they also have the natural experiment of the Northern Connectivity Event (2018) and Northern Fish Flow (2019) environmental water releases with similar volumes of water released under different antecedent conditions.

Both these catchments have rainfall above 800 mm/yr in their headwaters with a decrease in rainfall downstream to below 500 mm/yr at their confluence with the Barwon River. There are dams in the headwaters regulating the supply of water for irrigation further downstream within the catchments (Figure 2). The headwater streams are often gaining systems and as the alluvium get wider the streams become losing systems (Figure 1a) and predominately intermittent in their flow regime (Figure 1b). The waterholes and wetlands within these intermittent reaches are valuable refugia for biota in times of drought and are targets for environmental water.

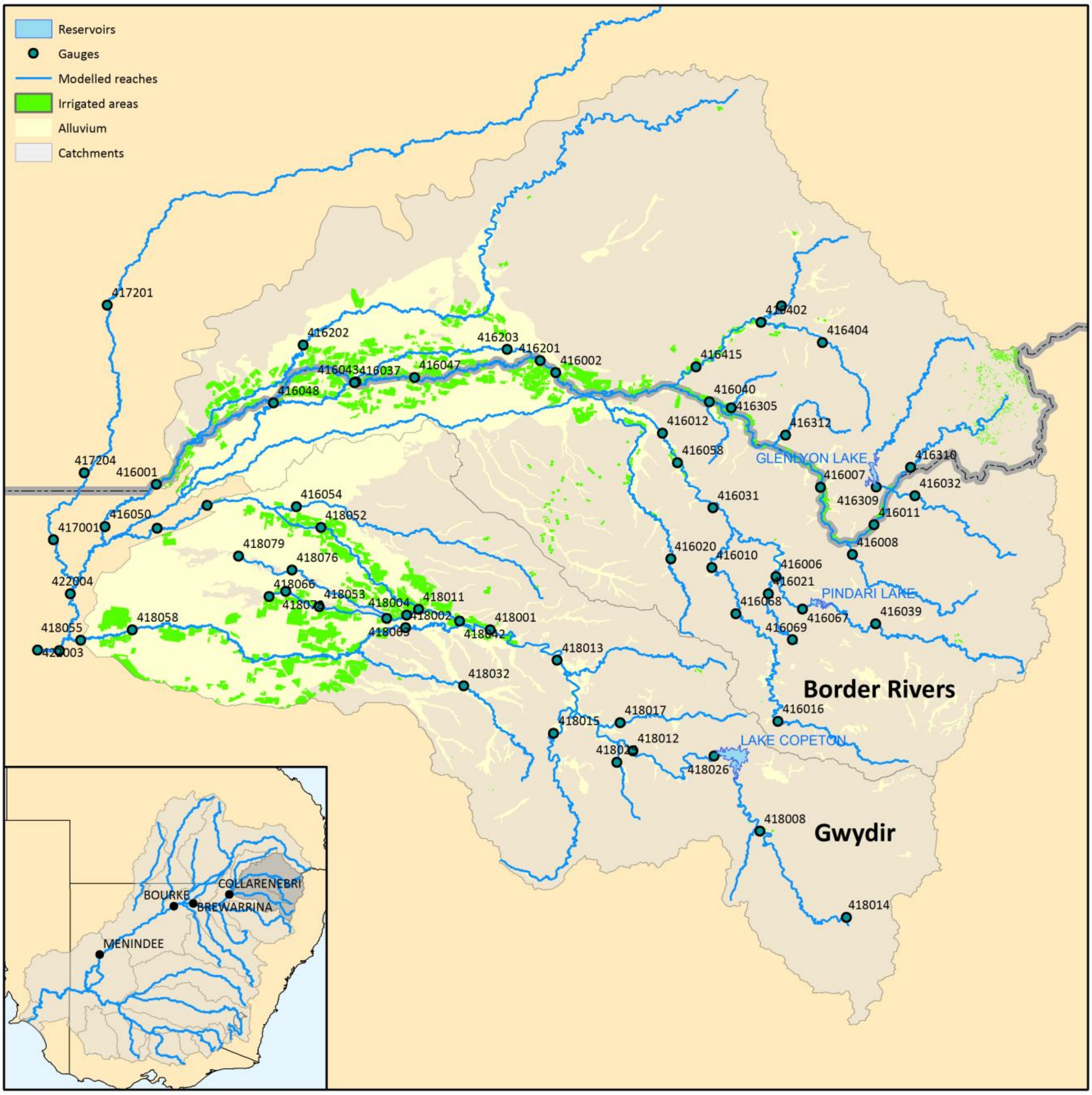

Figure 2 Case study catchments of the Gwydir and Border Rivers catchments. Inset shows location of these catchments within the MDB.

In January 2018, 1000 km of the Barwon-Darling River system had ceased to flow downstream of Brewarrina (Figure 2 inset). In March that year, rainfall in Queensland produced flows as far as Bourke, but the reaches further downstream remained dry. The Northern Connectivity event was a joint release of water held by the Commonwealth Environmental Water Holder (CEWH) and the New South Wales Office of Environment and Heritage (OEH) from Glenlyon Dam into the Dumaresq River (4.3 GL) and Copeton Dam into the Gwydir River (18.9 GL). This event released 23.2 GL of water over the course of a month from mid-April to mid-May in 2018. These environmental flows were protected from extraction to maximise the environmental benefits attainable. This event resulted in over 2000 km of stream connectivity in the Barwon-Darling system down as far as Menindee Lakes (DAWE, 2018).

The Northern Fish Flow event released 36 GL of water from Glenlyon and Copeton dams from April to June 2019. This water was released into a dry bed in the Barwon-Darling system as it did not have the benefit that the 2018 Northern Connectivity Event had in the earlier flows from Queensland. Even though more water was released in 2019 than in 2018, the distance the water travelled was substantially less. The flow from Glenlyon dam did not reach the Barwon at Collarenebri whereas the larger flow from Copeton Dam flowed beyond Brewarrina. It was estimated that the transmission losses from Collarenebri to Brewarrina were 5 times larger for the 2019 event compared to the 2018 event due to the antecedent conditions of empty river bed storage and waterholes (CEWO, 2019).

These two well documented flow events provide a natural experiment that will be difficult for a river systems model to replicate if it does not represent the physical processes involved in transmission losses. These two events will be a focus of the testing of the new water exchange function developed in this project.

3 Methods

In the first year of RQ6, the surface water – groundwater interactions analysis identified that the groundwater levels are falling across the MDB and that the losses are proportional to the difference in the elevation of the surface water and the groundwater (Crosbie et al., 2022b, Crosbie et al., 2023). To enable the representation of losses in river systems models as a function of changes in groundwater levels, some tracking of the groundwater store will be necessary. Similarly, the increase in intermittency (Crosbie et al., 2022a) requires the antecedent conditions to be tracked in the store of water in the river bed and banks. After cease to flow, this storage will become depleted and the storage deficit will need to be overcome to enable the river to flow again. Better representation of these physical processes in river systems models has been the focus of work in year 2 of RQ6 aimed at better predictions of low flows in the MDB. This is achieved by dynamically modelling the groundwater storage in the alluvium.

3.1 Selection of model code

The AWRA-R model code (Dutta et al., 2015) has been chosen as the starting point for this work. This is a node-link river systems model that was designed to be relatively simple to run. It lacks complexity around water sharing rules and dam operations that makes it unsuitable for use in water resources planning but uses the same basic structure and river routing as the models that are currently used for water resources planning such as Source (Welsh et al., 2013) and IQQM (Simons et al., 1996). It is envisioned that a new water exchange function developed for AWRA-R can be transferred to any other river systems model to replace the existing loss function.

The model was run with a conventional piece wise linear loss function and a new function with better representation of the physical processes occurring during river losses.

3.2 A new loss function for river systems models

3.2.1 River reach losses with dynamic storage and depth to groundwater

A flux-based method is used to model the leakage of a river over a variably sized near-river storage in AWRA-R. In the current description there are three potential throttles on leakage from flow in a river reach to underlying sediments: (i) flow through a low permeability riverbed, (ii) flow to an adjacent aquifer, and (iii) available storage volume in underlying sediments. From a purely water balance perspective the implicit fourth constraint is the total volume of flow in the reach.

In the description the daily loss is calculated as the minimum of either the potential loss through the riverbed, or the sum of the aquifer flow and available storage. This is derived from overbank flood recharge estimates by (Doble et al., 2012) and extended to within-channel river losses. In the original AWRA-R model there was the option to have variable depth to water as part of the storage and aquifer equations, but this was a fixed input rather than being computed internally.

To build a river loss model with a dynamic storage component, a water balance can be used. The three existing equations that can be re-used are:

$$\boldsymbol{I_{riv} = K_{riv}\, X_{riv} \left(\frac{H_{riv}}{D_{riv}} + 1\right) T\, L} \qquad \text{Equation 1}$$

$$\boldsymbol{S_{riv} = D_{gw}\, SY\, X_{riv}\, L} \qquad \text{Equation 2}$$

$$\boldsymbol{Q_{aq} = K_{aq}\, D_{aq}\, T \frac{H_{riv}}{X_{riv}/2}\, L} \qquad \text{Equation 3}$$

where:

- I_{riv} is infiltration from the river (m^3 timestep^{-1}),
- K_{riv} is hydraulic conductivity of riverbed (m s^{-1}),
- H_{riv} is depth of river flow (m, from depth-flow relationship),
- D_{riv} is thickness of riverbed layer (m),
- X_{riv} is width of river flow (m, from width-flow relationship),
- T is length of timestep (s),
- L is length of reach (m),
- S_{riv} is available storage below the river (m^3),
- D_{gw} is depth to groundwater (m),
- SY is specific yield below riverbed (dimensionless),
- Q_{aq} is discharge from the aquifer (m^3 timestep^{-1})
- K_{aq} is hydraulic conductivity of aquifer (m s^{-1}),
- D_{aq} is thickness of the aquifer (m),
- the actual river leakage Q_{gw} is the minimum of the volumes represented by I_{riv} and S_{riv} + Q_{aq}.

Within the existing set-up for AWRA-R, the flow in the river reach controls the relationships (and therefore values) of H_{riv} and X_{riv}, while K_{riv}, K_{aq}, D_{riv}, D_{aq} and SY may be either fixed by other data sources or fitted as necessary. Additional parameters and equations are required to manage a water balance to estimate the only remaining parameter which is D_{gw}; in the original set-up this value is a fixed temporal sequence, or it may simply be constant.

3.2.2 Alluvium as river storage (AARS)

If there is a conceptual alluvial deposit that a river reach is contained within, this storage volume can be modelled with a water balance within the existing AWRA-R code (Figure 3). This can then be used to dynamically compute D_{gw} instead of using user-determined values as in the original AWRA-R configurations. The additional parameters required to describe the alluvium are average width X_{alv} (m), average thickness D_{alv} (m) and current storage S_{alv} (m^3). The total potential storage in the alluvium is:

$$\boldsymbol{SM_{alv} = X_{alv}\, D_{alv}\, SY\, L} \qquad \text{Equation 4}$$

where SM_{alv} is maximum storage in alluvium (m^3). The dynamic value of depth to groundwater is:

$$\boldsymbol{D_{gw} = D_{alv}\left(1 - \frac{S_{alv}}{SM_{alv}}\right)} \qquad \text{Equation 5}$$

so when the alluvium is empty at $S_{alv}=0$ the depth to groundwater is the full thickness of alluvium, and when the alluvium is full at $S_{alv}=SM_{alv}$ the depth to groundwater is zero and there is no available storage.

There must be no confusion between X_{riv} and X_{alv}, as the flowing river width must be less than the total alluvium width. A possible variation in Eqn.4 is that the river width that leaks is equal to the flowing river width plus a buffer, in effect approximating a mound below the river rather than a simple rectangle. It is also worth noting that the potential storage for river leakage is only that directly below the flowing area and not the entire alluvium. This also implies that in the next timestep the new depth to groundwater will be averaged across the alluvium, so that available storage can be a restriction on river leakage without filling the entire alluvium.

The alluvium storage is subject to inputs and outputs as part of the water balance. The two primary input fluxes are (i) diffuse recharge from rainfall, and (ii) point recharge from river leakage, while the primary output flux is evaporation. A second output flux could be discharge to the river, however this might be handled using riverbank and/or overbank computations. The storage in the alluvium must be updated daily by:

$$\boldsymbol{S_{alv}^{t+1} = S_{alv}^{t} + Q_{gw}^{t+1} + f(Rain^{t+1}) - g(Evap^{t+1}) - Q_{aq}^{t}} \qquad \text{Equation 6}$$

Where *t* refers to the previous timestep, *t+1* refers to the new timestep, Q_{gw} is leakage from the river to groundwater, Q_{aq} is the discharge of the alluvial aquifer, *Rain* is daily gross rainfall, *Evap* is daily potential evaporation, and *f()* and *g()* are new functions of existing inputs. Diffuse recharge as a function of gross rainfall should be subject to reductions from runoff calculations, and further throttling with a fitted coefficient if necessary. Evaporative losses would likely be a function of relative storage so that demand is reduced as groundwater drops further below the land surface. Possible functions are:

$$\boldsymbol{f(Rain) = \alpha\,(Rain - Runoff)} \qquad \text{Equation 7}$$

$$\boldsymbol{g(Evap) = Evap\left\{\exp\left(\frac{-D_{gw}}{\beta}\right)\right\}^{\gamma}} \qquad \text{Equation 8}$$

where β is a fitted coefficient, while α and γ can either be fitted or omitted by setting to 1. *Runoff* is calculated prior (by AWRA-L or other rainfall runoff model), *Rain* and *Evap* are existing inputs. Note when α = 1 then diffuse recharge is equal to net rainfall. Note that both α is between zero and one, while β is greater than zero. When $\gamma = 1$, β may represent the riparian zone rooting depth.

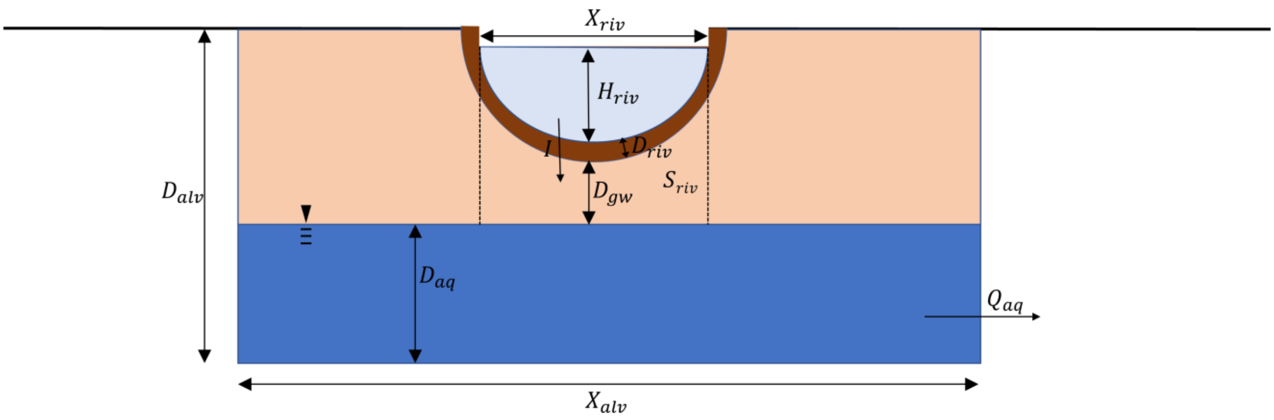

Figure 3 Cross-section diagram of conceptual alluvium as river storage.

3.2.3 Order of calculation

Where there is sufficient bore data, use the recorded depth to groundwater as an input for D_{alv}. If there is little groundwater data, then the alluvium model can be used but fitted against these data. When using the alluvium as a storage for river leakage, calculations involving storage and leakage need to be added at the correct locations.

- Before the groundwater leakage is calculated, generate D_{gw} from alluvium storage (Eqn.5).
- After the reach outflow is calculated, update S_{alv} with Q_{gw} and other fluxes (Eqns.6-8).
- Strict checking must be applied to S_{alv} so it does not exceed SM_{alv} due to diffuse and point recharge, or go below zero due to evaporation.

3.2.4 Future considerations

- There is no indication at this time of interaction, if any, between alluvium as a local groundwater store and regional groundwater.
- The river leakage Q_{gw} is the only component that should be reported externally in a water balance.
- If alluvium water levels are available however limited, they may provide useful insight into the dynamics of the storage and help fit the parameters in Eqn.7 and Eqn.8. River gauging data may likewise provide information about the timing of alluvium filling and emptying.
- There is no useful way to quantify bi-directional exchange between the river and alluvium. A threshold depth as used in MODFLOW river and drain package might be used to switch the sign of the flux based on a head difference.
- Considering the geometric mound of leakage in Figure 4, the buffer added to river width might be twice the sum of river stage and depth to groundwater.
- If depth to groundwater is strictly depth below riverbed, then the mound in Figure 4 would extend from the base of the river and not land surface. This would mean the river width buffer would only be twice the depth to groundwater. It would also imply that once the storage reaches the base of the river that no more leakage occurs, and bank flow storage and return would occur on the scale of a single timestep. This would not allow for the alluvium storage to provide return flow to the river.

- Data regarding baseflow (e.g., temperature or chemical tracers), or simply mathematical baseflow separation, may provide insight on the volumetric scale and timing of any return flow from the alluvium storage.

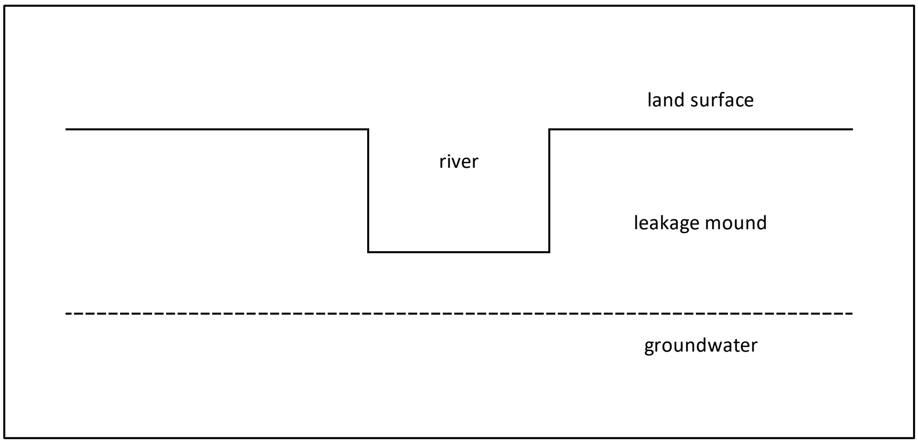

Figure 4 Conceptual groundwater mound created by leakage from river above groundwater

3.3 Loss function testing in the Border Rivers

Testing of the new loss function involved the calibration of the Border Rivers Catchment river system model originally built in AWRA-R. A piece wise linear loss model was used as a benchmark where the objective was to use the new model to improve benchmark low flow fit metrics without degrading medium/high flow fit performance.

3.3.1 Study site

Figure 2 shows the location of the Border Rivers in relation to the MDB. The current study utilised the AWRA-R version 5.0 Border Rivers network (Dutta et al., 2015). The reaches of the river system model are displayed in Table 1. Headwater reaches (opposed to residual reaches) are those that do not have an upstream gauge. The river system model consists of 14 headwater reaches, 18 residual reaches and four of these reaches include irrigation models for surface water extractions and two reaches contain reservoirs: 416309 (Glenlyon Dam) and 416019 (Pindari Dam).

Table 1 Details of the Border Rivers reaches used in the current study.

REACH ID	MAIN OUTLET NAME	UPSTREAM GAUGE	DOWNSTREAM GAUGE	HEADWATER	CONTAINS DAM	CONTAINS IRRIGATION	REACH AREA (km²)
416002	Macintyre@Boggabilla	416415, 416040, 416036, 416012, 416020	416002, 416002002	FALSE	FALSE	FALSE	1863
416006	Severn@Ashford	416019, 416021	416006	FALSE	FALSE	FALSE	278
416007	Dumaresq@Bonshaw Weir	416011, 416008	416007	FALSE	FALSE	FALSE	844
416008	Beardy @ Haystack		416008	TRUE	FALSE	FALSE	908
416011	Dumaresq@Roseneath	416309, 416310, 416032	416011	FALSE	FALSE	FALSE	1312

416018	Macintyre @ Dam site	416006, 416010	416018	FALSE	FALSE	FALSE	705
416020	Ottleys @ Coolatai		416020	TRUE	FALSE	FALSE	384
416021	Frasers Ck @ Westholme		416021	TRUE	FALSE	FALSE	813
416032	Mole @ Donaldson		416032	TRUE	FALSE	FALSE	1593
416036	Campbells Creek @ Near Beebo		416036	TRUE	FALSE	FALSE	313
416040	Dumaresq @ Glenarbon	416049, 416305	416040	FALSE	FALSE	FALSE	62
416043	Macintyre @ Boomi weir	416203, 416047	416043, 416037	FALSE	FALSE	TRUE	595
416049	Dumaresq @ Bonshaw	416007, 416312	416049	FALSE	FALSE	FALSE	1030
416305	Brush Creek @ Beebo		416305	TRUE	FALSE	FALSE	350
416309	Pike Creek @ Glenlyon Dam		416309	TRUE	TRUE	FALSE	1301
416310	Dumaresq@Farnbro		416310	TRUE	FALSE	FALSE	1292
416312	Oaky Creek @ Texas		416312	TRUE	FALSE	FALSE	393
416404	Bracker Creek @ Terraine		416404	TRUE	FALSE	FALSE	684
416407	Canning Creek @ Woodspring		416407	TRUE	FALSE	FALSE	1238
416001	Barwon@Mungindi	416048, 416202	416001	FALSE	FALSE	TRUE	1522
416010	Macintyre@Wallangra	416016	416010	FALSE	FALSE	FALSE	1376
416012	Macintyre@Holdfast (Yelarbon Crossing)	416018	416012	FALSE	FALSE	FALSE	879
416016	Macintyre@Inverell (Middle Ck)		416016	TRUE	FALSE	FALSE	751
416019	Severn@D/S Pindari Dam	416039	416019	FALSE	TRUE	FALSE	372
416028	Boomi @ Neeworra	416002002, 416037	416028	FALSE	FALSE	FALSE	5962
416039	Severn@Strathbogie		416039	TRUE	FALSE	FALSE	1748
416048	Macintrye@Kanowna	416043	416048	FALSE	FALSE	TRUE	945
416201	Macintyre @ Goondiwindi	416002	416201	FALSE	FALSE	TRUE	34
416202	Weir@Talwood		416202	TRUE	FALSE	FALSE	11756
416047	Callandoon Creek @ Carana Weir	416201	416047, 416203	FALSE	FALSE	FALSE	671
416402	Macintyre Brook@Inglewood	416404, 416407	416402	FALSE	TRUE	FALSE	1538
416415	Macintyre Brook @ Booba Sands	416402	416415	FALSE	FALSE	FALSE	675

3.3.2 Input data

Climate data

Rainfall and evapotranspiration data are required for each reach to run the rainfall runoff model and compute river fluxes. Gridded climate data was collected from the Australian Water Availability Project (AWAP) (http://www.csiro.au/awap/). The gridded data was aggregated to produce daily mean rainfall and evapotranspiration time series for each reach subcatchment.

Streamflow data

Observed streamflow data was collected from the Bureau of Meteorology's (BoM's) Water Data Online tool (http://www.bom.gov.au/waterdata/). This is matched by simulations of reach discharge (outflow) during calibrations to tune the model parameters. Additionally, observed streamflow data is used as inflows for the residual reaches.

During simulation, the river system model is run sequentially from the headwater reaches downstream to the lowest point of the network. This sequential simulation is important since it allows simulated flows to be transferred to downstream reaches. However, this also causes propagation of errors downstream which can be detrimental during calibration. Since there were generally decent streamflow records (> 10 years) for the gauges within the network, observed data were used as the inflows for each reach during calibration (where available). Any gaps in the observed streamflow record were patched with the upstream reach simulations.

Reservoir data

As in the streamflow data, the reservoir volume and area data for Glenlyon and Pindari Dams were collected from BoM's Water Data Online tool (http://www.bom.gov.au/waterdata/). These were processed to produce reservoir volumes and areas which are required for AWRA-R reservoir computations.

Irrigation model data

As mentioned, four reaches have irrigation modules that are run to account for significant river extractions. The current study used previously calibrated irrigation module parameters (Dutta et al., 2015). Time series data was extended to the current full calibration period by continuing annual patterns and predicting allocations based on fitted relationships between existing allocation data and reservoir volumes.

3.3.3 Warm-up, calibration, and validation periods

The full simulation period was from 1/1/1970 to 17/8/2022. Calibration was performed on a reach if more than five years of streamflow observations was available at the outlet gauge to calibrate against. In addition to this, split-sample calibration/validation was employed if more than 10 years of observed streamflow data was available at the outlet gauge. The full simulation period was divided such that half the observed outlet gauge streamflow is shared between each period. Calibrations were performed on each period and validated on the other. Each calibration/validation period excluded a warm-up period of 3 years at the beginning of each simulation.

3.3.4 Optimisation scheme

The Differential Evolution algorithm was used to calibrate each reach from the R package DEoptim (Ardia et al., 2011).

3.3.5 Piece wise linear (PWL) model benchmark calibration

Model configuration

The configuration of the reach models in the current study was similar to that used in (Dutta et al., 2015). The differences are:

- The original loss function in AWRA-R is replaced by the piece wise linear (PWL) loss function.
- In the current study, the rainfall runoff component is simulated using GR4J (Perrin et al., 2003) instead of using AWRA-L (Vaze et al., 2013) outputs.
- The full calibration period is from 1970 to 2022.

The PWL model is composed of six loss values at evenly spaced flow quantile intervals (Figure 5). Loss monotonically increases with rising flow quantile, and in between quantile intervals, losses are linearly interpolated. When modelled flows are outside the flow quantile intervals, losses are linearly extrapolated using the closest two points of the PWL curve. The six loss values are taken as the parameters for the PWL curve.

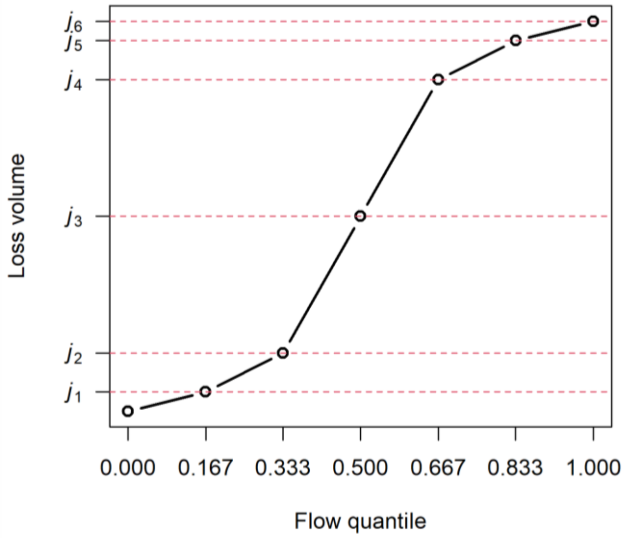

Figure 5 Illustration of the piecewise linear flow vs loss relationship with six parameters (j_1,…,j_6)

Calibrated parameters

The number of calibrated parameters for the benchmark residual reach model was 12 which includes 2 river routing parameters (routing timing parameter and a factor that weights between lag and Muskingum routing (Gill, 1978)), 4 GR4J parameters and 6 parameters for the PWL model. For headwater reaches the total number of calibrated parameters was 10 since they exclude the two routing parameters.

The lower and upper bound for each PWL parameter is defined by the corresponding flow quantile. That is, for i = 1,…,6:

$$l_i = \text{quantile}(Q_{obs}, i/6) \quad \text{Equation 9}$$
$$u_i = \text{quantile}(Q_{obs}, (i+1)/6) \quad \text{Equation 10}$$

where *l* and *u* are the lower and upper bounds, respectively, and Q_{obs} is the observed streamflow vector. Table 2 contains the ranges for the remaining calibrated parameters.

Table 2 River routing and GR4J rainfall runoff parameters.

PARAMETER	DESCRIPTION	LOWER VALUE	UPPER VALUE
ϕ	Routing timing parameter (s/m)	0.1	10
τ	Factor that weights between lag and the Muskingum routing	0	1
x_1	Maximum capacity of the production store (mm)	1	10000
x_2	Groundwater exchange coefficient (mm)	-30	30
x_3	1 day ahead maximum capacity of the routing store (mm)	1	1000
x_4	Time base of unit hydrograph 1 (days)	0.5	5

Objective function

The objective function used for the benchmark model is computed by the mean difference of Box-Cox transformed simulated and observed streamflow and incorporates a bias penalty:

$$bcbias_{PWL} = M\left(\frac{(Q_{obs}+1)^{\lambda}-1}{\lambda} - \frac{(Q_{sim}+1)^{\lambda}-1}{\lambda}\right)\left(1 + \left|\frac{M(Q_{sim})-M(Q_{obs})}{M(Q_{obs})}\right|\right) \quad \text{Equation 11}$$

where o_{PWL} is the objective function score and λ is the Box-Cox parameter (λ = 0.5). Q_{obs} and Q_{sim} are the observed and simulated streamflow vectors, respectively. *M*() is the function that computes the mean of a vector.

3.3.6 Alluvium as river storage (AARS) model calibration

Model configuration

The configuration of the reach models in the current study was similar to that used in (Dutta et al., 2015). The differences are:

- The original loss function in AWRA-R is replaced by the AARS model.
- In the current study, the rainfall runoff component is simulated using GR4J (Perrin et al., 2003) instead of using AWRA-L (Vaze et al., 2013) outputs.
- The full calibration period was from 1970 to 2022.

A depth to regolith map from Geoscience Australia (GA) (https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/75626) was used to produce D_{alv} for each reach by computing the mean of the cells within a 50 m buffer of the river network.

Calibrated parameters

The number of calibrated parameters was consistent with the PWL model; 12 residual reach parameters including 2 river routing parameters, 4 GR4J parameters and 6 parameters for the AARS model (X_{alv}, SY_{aq}, $K_{sat,aq}$, D_{riv}, $K_{sat,riv}$, β). Similar to the PWL model, headwater reaches exclude the 2 routing parameters. The river routing and GR4J parameter ranges are given in Table 2. The AARS model parameter ranges are given in Table 3.

Table 3 Calibrated parameters for the AARS model.

PARAMETER	DESCRIPTION	LOWER VALUE	UPPER VALUE
X_{alv}	Alluvium average width (m)	1	100
SY_{aq}	Aquifer specific yield of the aquifer	10^{-6}	0.4
$K_{sat,aq}$	Aquifer saturated conductivity	10^{-14}	$10^{-1.7}$
D_{riv}	Riverbed layer thickness (m)	10^{-3}	3
$K_{sat,riv}$	Riverbed saturated conductivity	10^{-14}	$10^{-1.7}$
β	Rooting depth (m)	10^{-4}	50

Objective function

The objective function used to calibrate the AARS model weights low flow fit but utilises the corresponding reach's benchmark objective function score to heavily penalise any degradation in medium/high flow fits and bias. The low flow fit objective function is given by:

$$lowfit = M(\{\log(Q_{obs} + \varepsilon) - \log(Q_{sim} + \varepsilon)\}^2) \quad \text{Equation 12}$$

where ε is the minimum observed streamflow value above zero. This is to prevent performing log of zero. Let $bcbias_{AARS}$ be the benchmark objective function (Eqn.11) computed for the AARS model simulation. The objective function used to calibrate the AARs model is:

$$lowfitwithpenalty = lowfit \times \max\left(100^{(bcbias_{AARS} - bcbias_{PWL})}, 1\right) \quad \text{Equation 13}$$

4 Results and discussion

Calibration and validation results are compared for five different fit metrics. Firstly, the benchmark objective function was compared to ensure that the penalty function employed in AARS model calibration is performing as expected. Figure 6 shows that all reaches perform similarly between the PWL and AARS, although in the full period calibration and calibration period 1 there are some reaches which perform slightly worse for AARS than PWL. Interestingly, AARS performs better than PWL for some reaches in validation period 1 despite obtaining slightly worst fits during calibration. AARS performs very similarly to PWL in calibration period 2 but PWL performs better than AARS in validation period 2.

Nash-Sutcliffe Efficiency is known to place more importance on medium and high flows and was examined here to identify any significant effects caused by AARS (Figure 7), especially since the calibrations do not explicitly place importance on this metric. Generally, there was little reduction in NSE, however, poorer comparative NSE scoring reaches tended to be amplified when AARS model results were already poor.

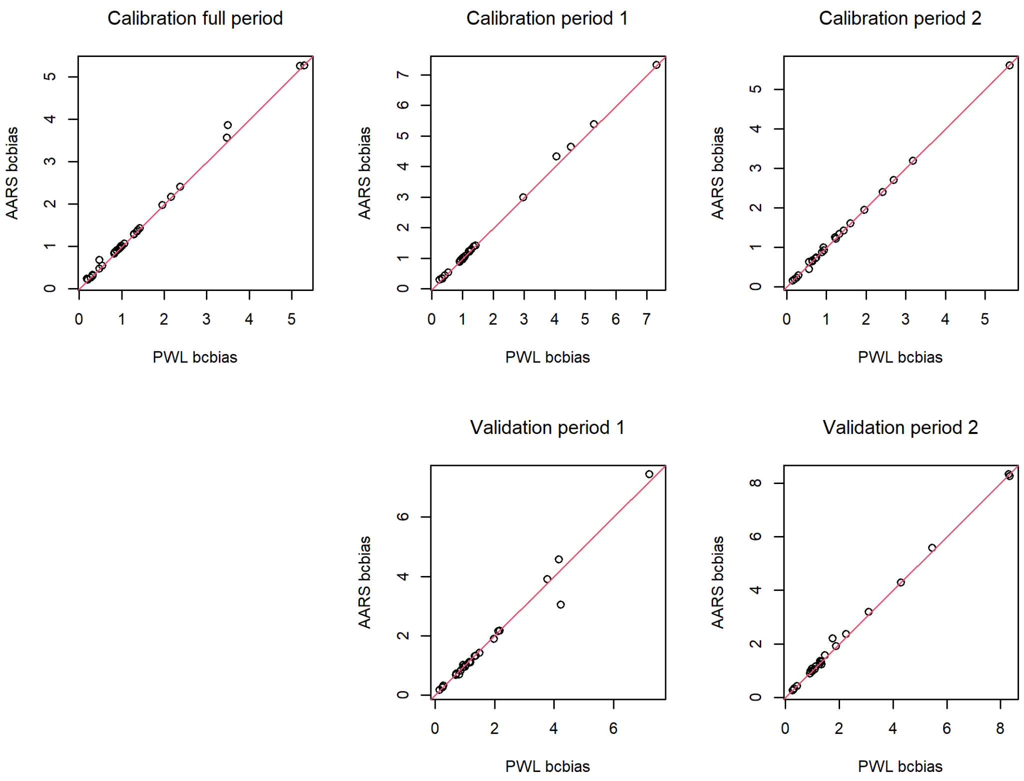

Figure 6 Calibration and validation fit performance comparisons for the benchmark objective function, bcbias (lower is better).

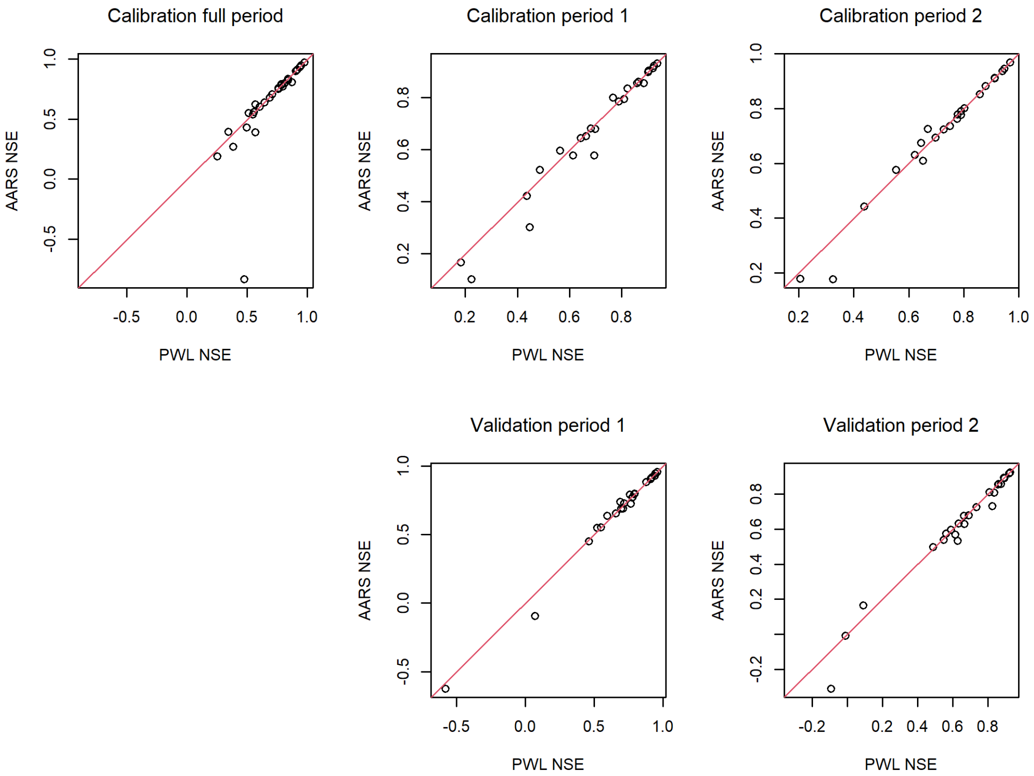

Figure 7 Calibration and validation fit performance comparisons for Nash-Sutcliffe Efficiency, NSE (higher is better).

Nash-Sutcliffe Efficiency on square root transformed flow is an important metric as this transformation plays an important role in the benchmark objective function. The AARS clearly outperforms the PWL model in both calibration and validation, particularly when only poorer values are achieved (Figure 8).

The penalty within the objective function used for the AARS model calibration does not seem to always maintain biases achieved by the benchmark (Figure 9). It is likely that bias is being traded off for the superior fit to square root transformed flows seen in Figure 8. Modifications to the AARS objective function could involve more explicit treatment of benchmark bias. Nonetheless, there are some signs that the PWL model overfits to bias in many reaches, shown by the improved AARS bias scores during validation period 1. Likewise, in validation period 2, more reach points appear closer to the 1:1 line than for calibration period 2.

Finally, the AARS model clearly shows superior fits to low flows compared to the PWL model over calibration and validation periods (Figure 10). Overall, the study of the reaches in the Border Rivers Catchment showed that the AARS model can produce improved low flow predictions over a PWL model. This is achieved without major reduction in other important flow metrics such as NSE. While calibration bias is somewhat degraded, this degradation reduces substantially during validation. Improved NSE (sqrt) could be compensating for poorer calibration bias and, thus, the AARS model obtains similar results to the benchmark metrics in the overall sense.

It should be noted that this comparative assessment assumes that adequate weight is given to low flows after performing a log transform to streamflow. This implies a relatively narrow definition of low flows. Future studies will involve metrics that encompass a wide range of low flow descriptions, for example, those characterised by frequencies or length of cease to flow events.

Further work involves modifying the AARS objective function to obtain more balanced performances between flow metrics. Next steps also involve analysis of the loss functions parameterisations, as well as model stores and fluxes to see if the model behaves as expected under different conditions. This is likely to guide future structural improvements.

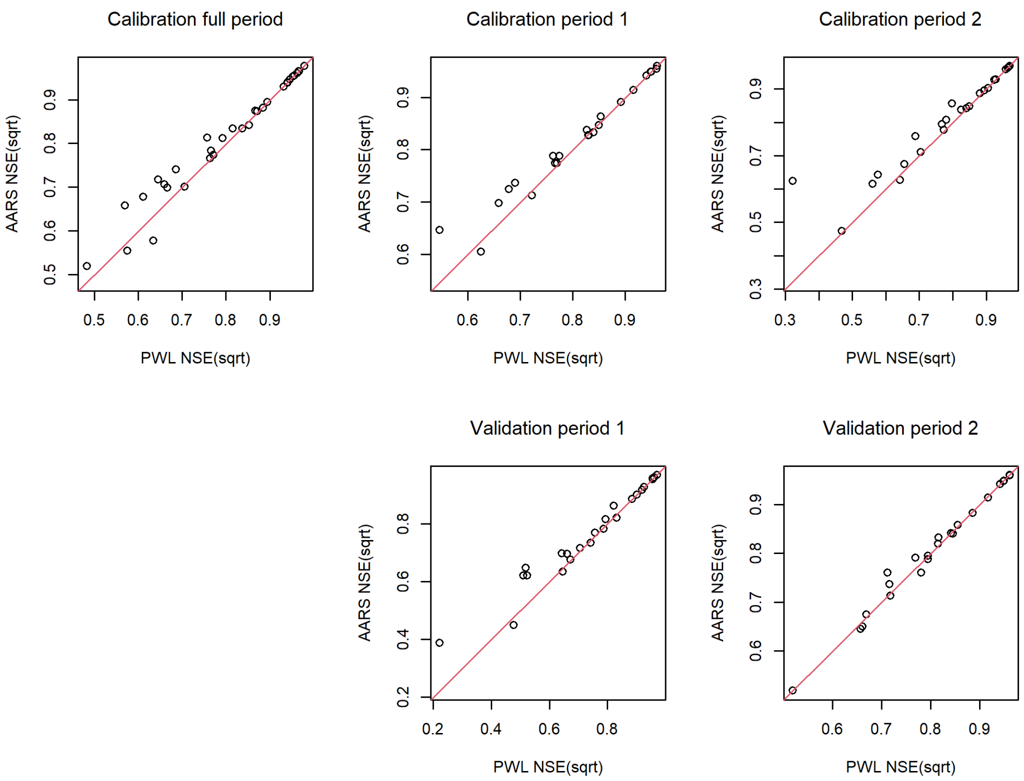

Figure 8 Calibration and validation fit performance comparisons for Nash-Sutcliffe Efficiency on square root transformed flow, NSE(sqrt) (higher is better).

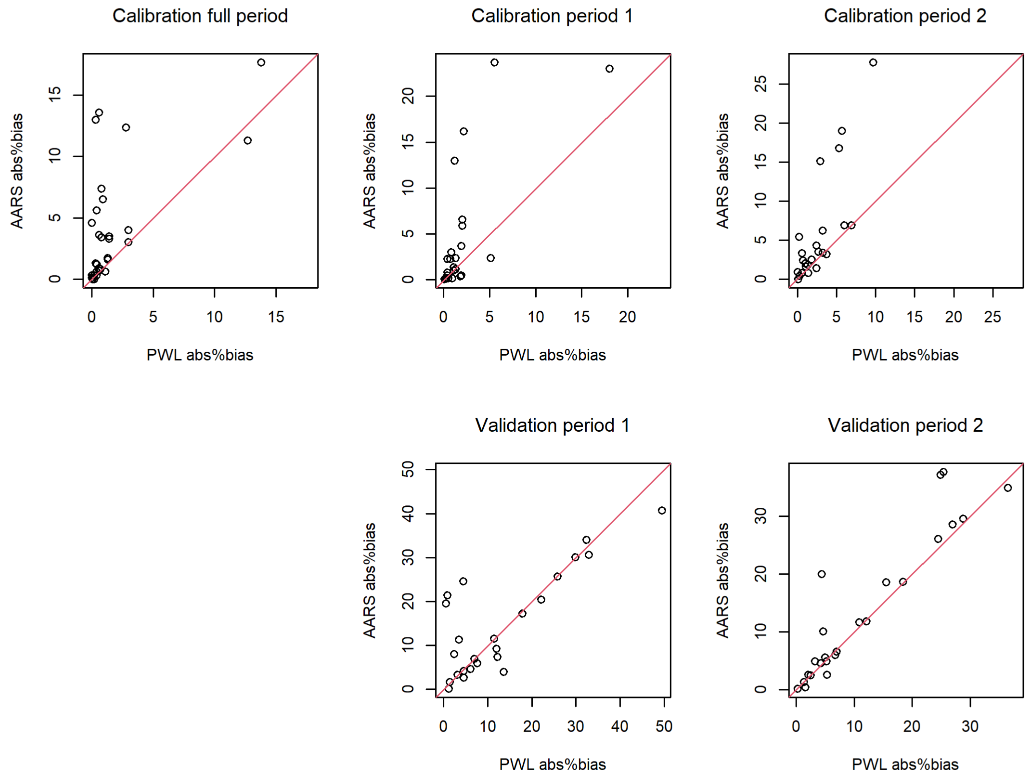

Figure 9 Calibration and validation fit performance comparisons for percentage bias, abs%bias (lower is better).

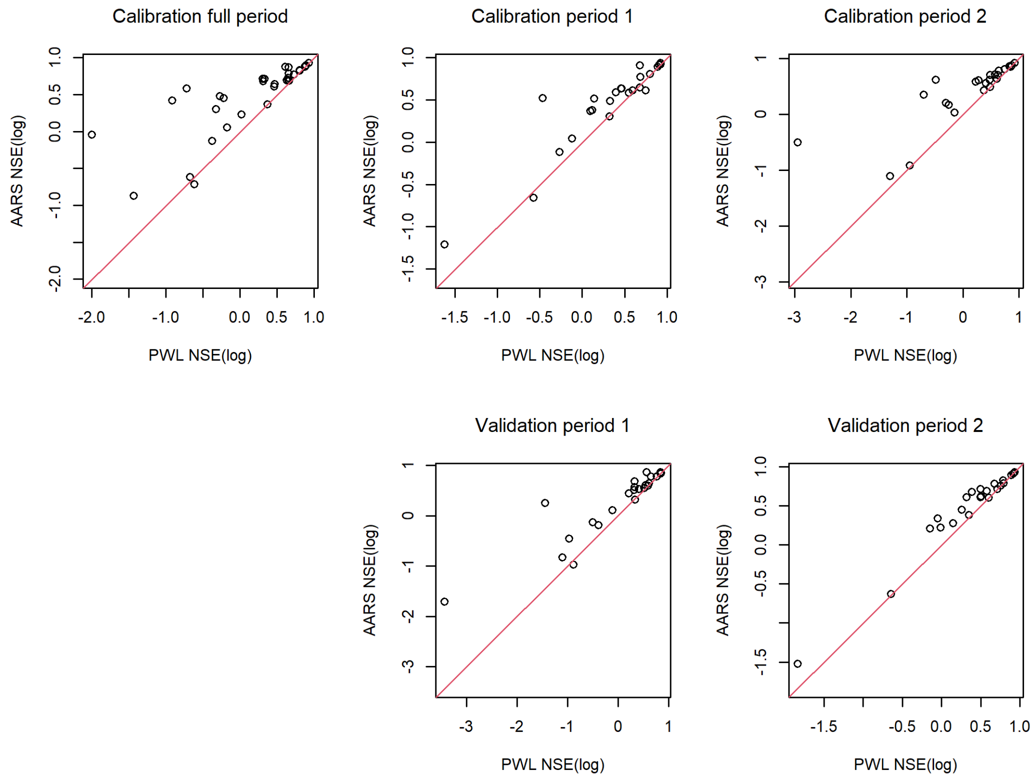

Figure 10 Calibration and validation fit performance comparisons for Nash-Sutcliffe Efficiency on log transformed flow, NSE(log) (higher is better).

5 Next steps

The RQ6 research in 2023/2024 will further improve and test the new water exchange function and quantify model improvement in simulating low flows. This will be conducted in the case study catchments of the Gwydir and Border Rivers and specifically looking at the Northern Connectivity Event (2018), Northern Fish Flow (2019) and Recommencement of flow in early 2020.

1. A sensitivity analysis will be conducted to determine how the parameters respond to both the calibration objective function and the flow metric (mainly low flow) of interest. The sensitivity analysis will help provide an understanding of the model responses and guide parameterisation of the model.
2. The case study for the new water exchange function will be carried out in the Gwydir and Border Rivers catchments. The Northern Connectivity Event (2018), Northern Fish Flow (2019) and Recommencement of flow in early 2020 in the Barwon-Darling provide some of the best controlled releases that have observed data and provide a contrast in their transmission losses for different antecedent conditions at the time. These events provide opportunistic datasets to test the new function. The new version of AWRA-R will be tested against the original version of the model (Dutta et al., 2015) and benchmarked against another version of the model (Kim et al., 2022), particularly for their low flow performance. This will be quantified through low flow metrics such as Q10, number of no flow days and the timing of cease to flow and start to flow events.
3. The model will also be tested in a perennial gaining river to ensure that the new loss function does not have any deleterious effects on flow simulations in catchments where it is not required.
4. Remotely sensed and/or field observations (maps of actual evapotranspiration, soil water holding capacity and surface layer hydraulic conductivity) will be incorporated to constrain the models and reduce the number of calibrated parameters.

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