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Assessing residual inflow and loss estimates methods in river reach calibration using the Budyko Framework

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Abstract: River system models are widely used for planning and management in river basins. In highly regulated systems, streamflow volumes in the river from upstream can be far greater than contributions from local runoff and the estimation of localized runoff will have little influence on model performance at the downstream gauge as assessed using metrics such as Bias and Nash-Sutcliffe Efficiency (NSE). However, the local runoff could have significant implications for regional water management. Local runoff, commonly referred to as residual inflows may provide important environmental flows or may supplement irrigation diversions via floodplain harvesting into on farm storages. The estimation of these residual inflows and their corresponding losses can be difficult since different combinations of estimated residual inflows and losses could give similar results at the downstream gauges in term of model performance. It is important that the estimation of both residual inflows and losses are constrained to values that are in line with our understanding on the upper and lower limits for runoff, as the estimated values can have significant management implications and therefore adequate representation of these components of the water balance are required in the river system models used for basin management.

This paper compared a range of schemes that could be applied to estimate losses and residual inflows during model calibration of the river reaches. The outputs from these methods were assessed according to the bounds of local runoff determined from the analysis of observed catchment runoff at the mean annual scale for 213 unimpaired streamflow sites in the Murray Darling Basin.

Three schemes to estimate reach losses based on the difference between the simulated and observed streamflow were tested. The three schemes were different in terms of the data used to derive loss functions, which includes (i) deriving loss function basing on the entire streamflow record, (ii) deriving loss function using only the days where upstream flows exceed downstream flow (losing periods), and (iii) deriving loss function according to periods with the lowest 20% rainfall or weekly rain less than 1 mm. To estimate the residual inflows, a rainfall-runoff model was calibrated to either the gauged streamflow or to the estimated residual flows, and the residual inflows in the reach were estimated either before or after a loss relationship was applied to the river reach model. This resulted in 12 different schemes for estimating residual inflows and the corresponding loss. These schemes were tested across seven regulated reaches, six in the Murray Darling basin and one in North Queensland.

Different schemes have provided different estimates for the magnitude of residual inflows. In order to assess which estimates of residual inflow were more realistic, the estimates were assessed by the mean annual runoff estimated using the Budyko framework (Budyko, 1958) , which assumes that mean annual evapotranspiration (ET) from a catchment will approach total precipitation (P) under very dry conditions (water limit) or potential evapotranspiration (E_0) under very wet conditions (energy limit). The schemes tested did not show a clear best method for the estimation of losses and residual inflows. Particularly, the use of the losing periods to define loss function tended to results in higher runoff coefficients and is potentially unrealistic as assessed via Budyko framework. In this case, the Budyko framework can provide a quick assessment and constrain of the magnitude of the residual inflow estimates.

Keywords: *Reach calibration, rainfall runoff modelling, Budyko framework*

1. INTRODUCTION

The development of the eWater Source (Welsh et al 2102) has provided a standardised modelling platform for use in modelling regulated river system in the Murray Darling Basin (MDB) and beyond. While such a platform is a useful first step in gaining consistency in the models that underpin water resource management, there are still many ways in which different components of the water balance can be estimated within eWater Source. To aid in the consistency in model implementation across the MDB, the Murray Darling Basin Authority (MDBA), the state jurisdictions, and the CSIRO are working together to develop a set of practice notes. These practice notes aim to outline the general principles that should be followed when building river system models to underpin water resource planning in the MDB.

For certain aspects of model building, it is possible to reach an agreement on a methodology to be adopted across practitioners from different organizations, in some instances achieving consensus on an agreed practice is not straightforward. In such cases, testing of alternative methodologies for a particular aspect of model building allows us to determine how different methods perform over a range of conditions. During the development of the practice notes, the estimation of runoff from the local catchment (residual inflows) and the corresponding loss relationships was identified as an area where there would be value in comparing current approaches used to estimate these unmeasured components of the water balance.

There are many different components of the water balance that must be considered during calibration of a river reach. The prediction of streamflow at the downstream gauge depends on upstream inflow, tributary inflows, routing, any explicit losses (e.g. irrigation diversions, net evaporation) and explicit gains such as tributary inflows and residual inflows (local runoff), plus an unaccounted difference component (Hughes, et al., 2014). The estimated residual inflows and the corresponding loss relationships may have impacts for water management, as local runoff may provide important environmental flows or may supplement irrigation diversions via floodplain harvesting into on farm storages. Therefore, adequate representation of these components of the water balance is required in the river system models used for basin management.

In highly regulated systems such as the Murray-Darling Basin (MDB), upstream streamflow volumes can be far greater than contributions from local runoff. In this situation, the estimation of localized runoff will have little influence on model quality as assessed using traditional metrics such as Bias and Nash-Sutcliffe Efficiency (NSE). However, the estimate of localized runoff is still required. Due to the complexity of hydrological processes, most hydrological models require calibration. In some of the reaches in the MDB this calibration is difficult because upstream and downstream volumes are much higher than localized runoff volumes. However, at longer time scales, simpler models can be used to predict an expected range for this localised runoff. One such model is the Budyko framework (Budyko, 1958) which assumes that mean annual evapotranspiration (ET) from a catchment will approach total precipitation (P) under very dry conditions (water limit) and potential evapotranspiration (E_0) under very wet conditions (energy limit). This framework has been used at the mean annual timescale to distinguish between catchments with different vegetation types (Zhang et al. 2001), and it can also be used to estimate mean annual runoff across Australia (Ting et al. 2012).

This paper compares a range of methodologies for estimating losses and residual inflows during reach calibration. It compares the outputs from these methods to bounds on local runoff as determined from the analysis of observed catchment data at the mean annual scale using the Budyko Framework.

2. METHODS

Seven test reaches were selected for use in this method assessment. These reaches cover a range of different conditions and complexity found in the MDB, but also include a reach in the Fitzroy catchment in Queensland. The locations of the seven test reaches are shown in Figure 1.

The methods for the assessment in this study were on the basis of a review of existing methodologies currently applied in the MDB by the MDBA and state agencies. According to the review, it was determined that three different methods for estimating losses and two methods for estimating residual inflows (calibration to gauge and to residuals) should be tested, and where possible the order of estimation should also be considered. The loss function in the form of inflow-loss relationships was derived by comparing the daily exceedance curves of the observed and simulated flows during a selected period. Therefore, the methods of deriving the loss functions were different as different periods were selected in this study, namely (a) the entire record during the calibration period (all record), (b) periods where upstream flows exceed downstream flow (losing periods), (c) periods where the lowest 20% rainfall or weekly rain is less than 1 mm (dry periods). In the loss functions, the losses were required to have a positive value (or at least constant).

2.1. Estimation of residual inflows using Source

The eWater Source was used to build catchments models for each test reaches, with each model including all known inflows, losses and routing. In all reaches a lumped loss node and residual inflow node were placed near the bottom on the reach, with two possible configurations, one for the loss node upstream of the residual inflow node, and the other for the loss node downstream of the residual inflow node. The residual inflow is simulated using the Sacramento rainfall runoff model (Burnash et al 1973). The model was calibrated using optimizer outside the Source platform. The residual inflows were calibrated against two different estimates, (1) the flows at the downstream gauge, and (2) a smoothed residual flow time series. The smoothed residual flow time series was generated by smoothing the negative parts of the time series of the difference between observed and simulated flow, which means that observation is less than simulation and possible losses exist.

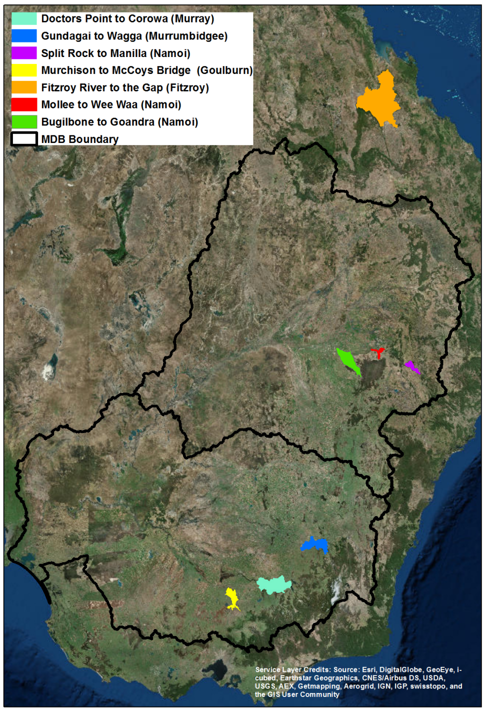

Figure 1. Location of test catchments

The Sacramento rainfall runoff model was calibrated using the SDEB (Sum of Daily Flows, Daily Exceedance (Flow Duration) Curve and Bias) objective function (Lerat et al. 2013):

$$SDEB = \left(0.1\sum_{i=1}^{N}\left(\sqrt[2]{Q_{obs}} - \sqrt[2]{Q_{sim}}\right)^2 + 0.9\sum_{i=1}^{N}\left(\sqrt[2]{R_{obs}} - \sqrt[2]{R_{sim}}\right)^2\right) * \left(1 + \frac{abs\left(\sum_{i=1}^{N} Q_{sim} - \sum_{i=1}^{N} Q_{obs}\right)}{\sum_{i=1}^{N} Q_{obs}}\right) \tag{1}$$

where N is the number of time steps, $Q_{obs,i}$ and $Q_{mod,i}$ are the observed and modelled flow for time step i, respectively, and $R_{obs,k}$ and $R_{sim,k}$ are the k'th ranked observed and modelled flow of a total of N ranked flows, respectively.

The use of three loss functions, two different orders of estimation (residuals or losses first) and two calibrations (gauge or residuals) resulted in 12 different schemes for estimating residual inflows and the corresponding losses relationship in each reach, plus two extra schemes for the calibration to either gauge or residual without using a loss node. Also, the available streamflow record in each reach was divided in two separate periods, and the model calibration/validation was done twice using split samples (Klemes, 1986), resulting in 28 possible scenarios for each reach. Following the incorporation of a lumped loss function and a residual inflow time series, the quality of the calibration was compared to a baseline or benchmark model. For this comparison, the baseline model was the simulation without lumped loss and residual inflow. Skills scores including Bias and NSE were calculated to assess model performance during both the calibration and validation period as compared to the benchmark model. The skills scores were calculated as:

$$NSE\ Skill = \frac{(NSE_{Scenario} - NSE_{Benchmark})}{(1 - NSE_{Benchmark})} \tag{2}$$

$$Bias\ Skill = 1 - \frac{abs(Bias_{Scenario})}{abs(Bias_{Benchmark})} \tag{3}$$

2.2. Estimation of mean annual runoff using the Budyko framework

On mean annual time scale, runoff can be estimated using the Budyko framework which can be considered similar to runoff prediction of ungauged basins (PUBs). According to the Budyko framework, if the annual runoff can be considered as the difference between annual precipitation (P) and actual evapotranspiration (ET), it can then be estimated when the mean annual precipitation and potential evapotranspiration (E_0) were known. Following the expression proposed by Fu (1981), the mean annual runoff (Q) can be estimated as:

$$\frac{Q}{P} = \left[1 + \left(\frac{E_0}{P}\right)^w\right]^{1/w} - \frac{E_0}{P} \tag{4}$$

where w is a model parameter related to catchment characteristics (Fu, 1981; Zhang et al., 2004). This means that one can provide estimates of residual flows using the Budyko framework when mean annual precipitation and potential evaporation are available.

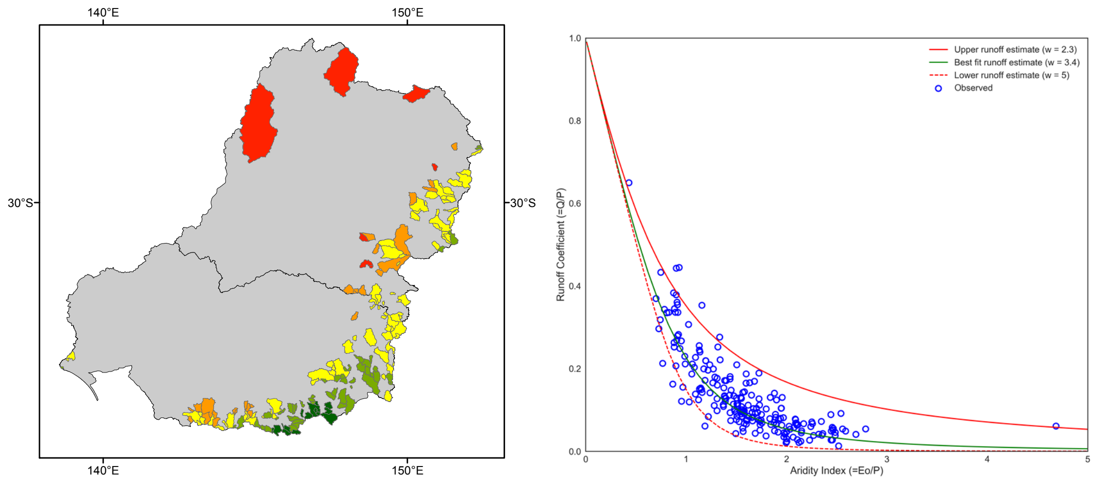

Figure 2. Map showing locations of selected catchments in the Murray-Darling basin (left) and Scatterplots of runoff ratio (Q/P) against the aridity index. Each point represents one catchment and lines are the relationships represented by Fu (1981) with different values of w parameter.

To test the feasibility of using the Budyko framework in estimating mean annual runoff, 213 catchments from the Murray-Darling Basin covering different hydroclimatic conditions were selected in this study(see Figure 2, left panel). The aridity index and runoff coefficient for the period 1965 to 2009 were calculated using SILO patched point data for rainfall and PET, and the results were shown in Figure 2 (right panel). It was clear that the runoff coefficient (Q/P) followed the Budyko relationship as represented by the Fu equation. The optimized value of parameter w is 3.4 for the region as a whole but varies between 2.3 and 5. The estimated value of w matched well with the reported value in the literature (Zhang et al., 2004), and was then used to provide a set of upper and lower runoff bounds that can be expected in the MDB.

Table 1. Abbreviation and details for each test case

Schemes	Abbreviation	Estimation order	Period of data used to derive loss function	Calibration to	Number of reaches where losses could be estimated
#01	ARL_RC	Loss First	Entire record	smoothed residuals	2 reaches
#02	LPL_RC		Losing period		7 reaches
#03	DPL_RC		Dry period		3 reaches
#04	ARL_GC		Entire record	Gauge	3 reaches
#05	LPL_GC		Losing period		8 reaches
#06	DPL_GC		Dry period		4 reaches
#07	RC_only	No Loss	N/A	Smoothed residuals	7 reaches
#08	GC_only	No Loss	N/A	Gauge	7 reaches
#09	RC_ARL	Residuals First	Entire record	Smoothed residuals	3 reaches
#10	RC_LPL		Losing period		7 reaches
#11	RC_DPL		Dry period		4 reaches
#12	GC_ARL		Entire record	Gauge	2 reaches
#13	GC_LPL		Losing period		7 reaches
#14	GC_DPL		Dry period		2 reaches

3. RESULTS AND DISCUSSION

It was not always possible to determine a valid loss relationship using the flow duration curves based on the entire record or the period defined by low rainfall. However, it was possible to determine a loss relationship using data from the losing periods. To provide a comparison between the schemes, herein, the results were only shown for reaches where at least two loss functions could be obtained. The analysis only considered the results from single iteration of losses and residual inflow estimation, although in practice, the estimation process may be repeated multiple times to achieve better model performance assessed by metrics like NSE, Bias or a priori runoff coefficient. The purpose to undertake a single iteration was to ensure consistent comparison of the schemes. It is possible that better metrics could be achieved by repeating the process on determination of losses and residuals. In all the test reaches, the SDEB, Bias and NSE were presented using skills scores compared to the benchmark scheme (named No_Loss_No_RI) for both the calibration and validation period. Table 1 showed the abbreviation to identify each of the 14 methods tested along with the number of reaches where it was possible to estimate a loss function. The results for the SDEB, NSE and Bias skill scores for all reaches and scenarios where at least two loss methods could be used were shown in Figure 3, Figure 4 and Figure 5, respectively.

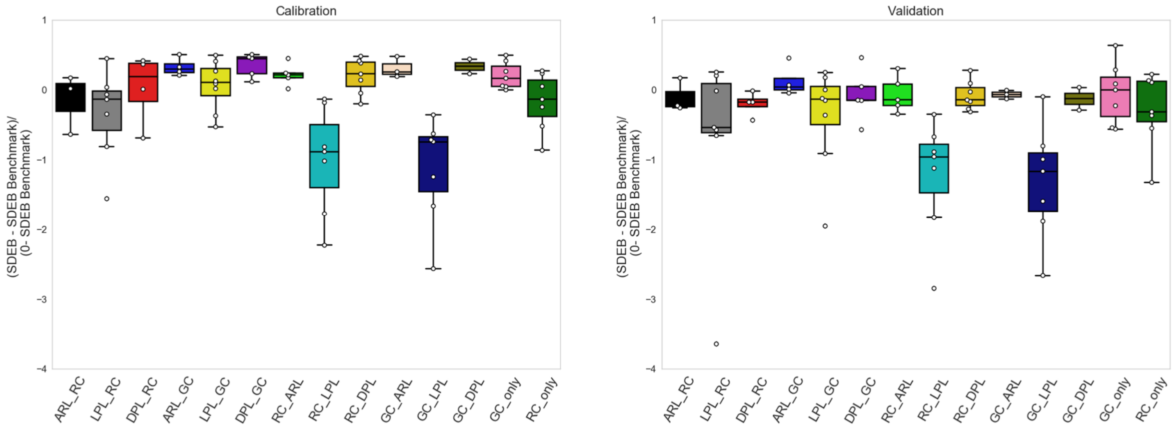

Figure 3. SDEB scores for all reaches and cases where at least two schemes of loss function deriving were used. Calibration period on the left panel and validation period on the right panel. The right dots represent the value of each available data point.

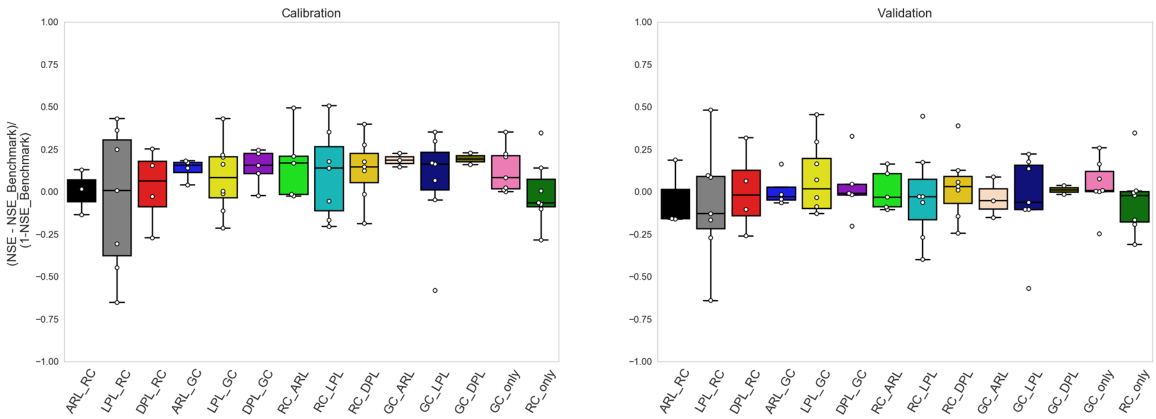

Figure 4. NSE scores for all reaches and cases where at least two schemes of loss function deriving were used. Calibration period on the left panel and validation period on the right panel. The right dots represent the value of each available data point.

In the Figures 3-5, the calibration results were for both periods, while the validation results were for the validation period only. The NSE, Bias and SDEB skill scores suggested that there was no scheme that always delivered better skill scores across all reaches. The SDEB and Bias of the scheme when calibrated using the loss function derived from the losing period showed particularly poor results, and it can be expected that such loss function would be rejected in normal practice. Although there was no clear best scheme, some schemes did show considerably more robust than others, particularly during calibration. The calibrations to the gauge and deriving loss function using either the entire record (ARL) or the dry period (DPL) showed significantly less variability. During validation, the same cases showed lower variability for NSE, but the Bias results did not show the same consistency.

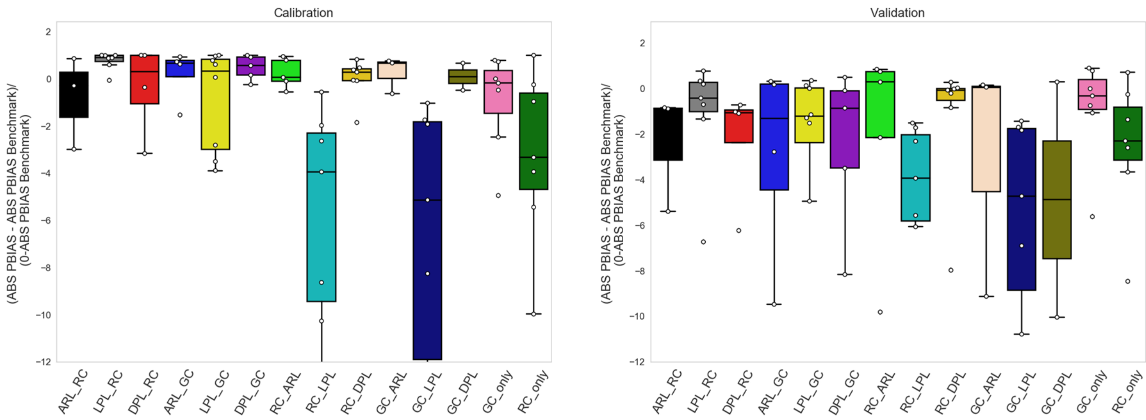

Figure 5. Bias scores for all reaches and cases where at least two loss methods were used. Calibration period on the left panel and validation period on the right panel. The right dots represent the value of each available data point.

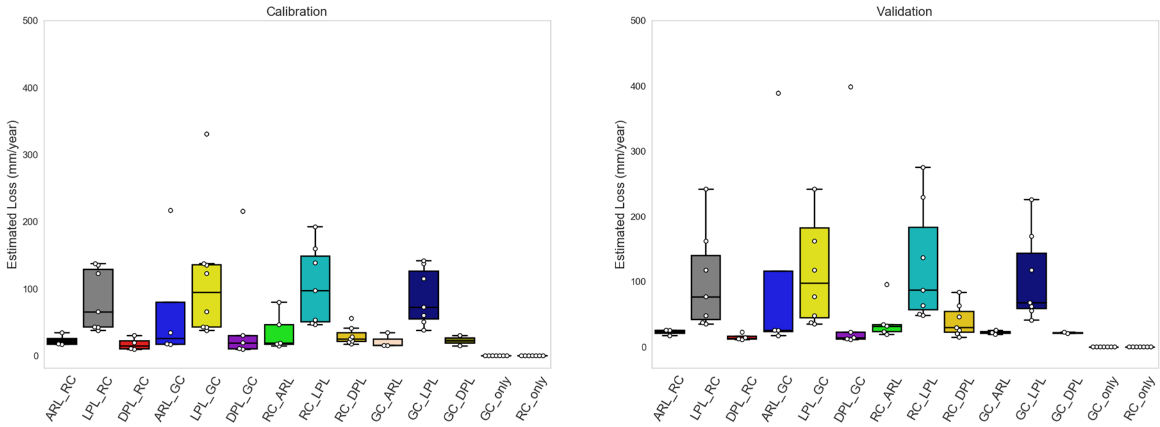

Figure 6. Estimated losses for all reaches and cases with at least two valid loss methods for the calibration (left panel) and validation (right panel) periods

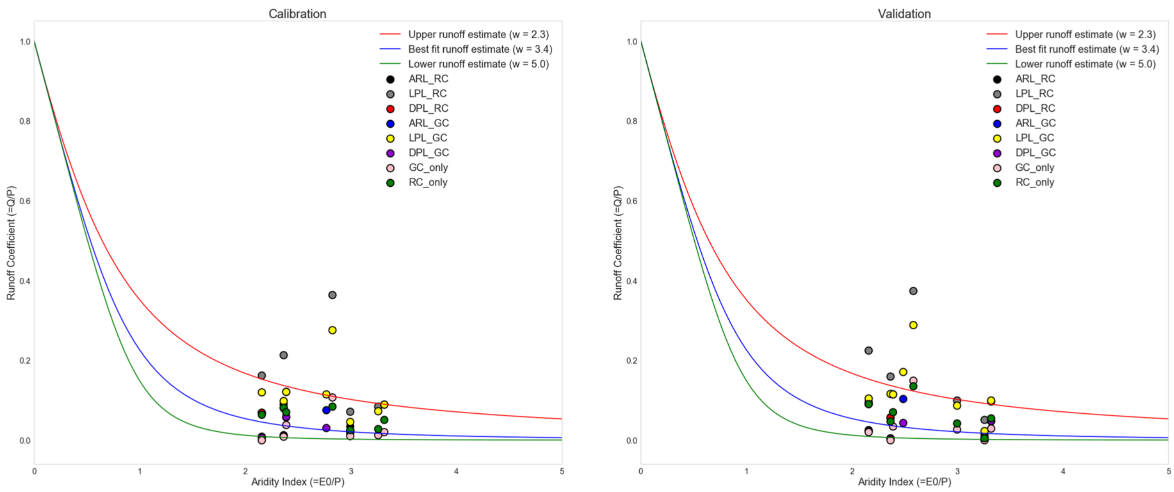

Figure 7. Runoff coefficients versus aridity for all reaches and cases with at least two valid loss methods for the calibration (left panel) and validation (right panel) periods.

Although the skill scores showed that all schemes can provide similar results in terms of model performance, an analysis of the components of the water balance showed that different schemes can lead to quite different estimates of the magnitude of residual inflows and losses. Besides the larger variability, the use of loss function basing on losing periods tended to result in much larger losses as shown in Figure 6. To compensate for the higher losses, the calibration of the rainfall runoff model resulted in a parameter sets that outputted much larger simulated residual inflow as compared to other schemes.

The residual inflows obtained from each scheme were then assessed by the Budyko framework to see if they sit in the boundaries obtained from the analysis of 213 gauged catchments in the MDB (shown in Figure 2, right panel). The simulated runoff coefficient regarding the residual inflow with relation to the aridity index were shown in Figure 7, where runoff coefficients estimated from some schemes were outside the suggested boundaries. Particularly, and the runoff coefficients estimated basing on the losing period schemes were reasonably high suggesting unrealistic residual inflow estimate.

4. CONCLUSIONS

The results shown here suggested that the use of the Budyko framework with lower and upper bounds based on the 213 unregulated catchments could provide a useful tool to have a quick assessment of the residual inflow estimates. The use of the Budyko framework also allowed for a model check even before losses and residual were being calibrated, as if it pointed to an unreasonable runoff coefficient, model input checking could be necessary before proceeding residual inflow estimation.

The methodology tested here did not show a clear best scheme to obtain estimates of residual inflows or losses. What it was clear though was that the use of the losing periods to define loss functions resulted in higher (and potentially unrealistic) runoff coefficients. If it was deemed the appropriate scheme for estimating loss in a reach, care must be placed on the influence the choice of loss period may have on the magnitude of the residual inflows. As the results for different reaches shown, it was possible to have reasonable model performance (based on the Bias) when using loss function basing on losing period, followed by calibration of residual inflows. The use of loss function from losing periods could potentially result good model performance, but along with unrealistic high residual inflows and losses that compensate for each other. In this case, the Budyko framework was especially helpful in providing a quick assessment and constrain on the magnitude of the residual inflows.

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