

Towards a semi-asynchronous method for hydrological modelling in climate change studies

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The paper of Talbot et al. addresses the topic of climate change hydrological projections, and specifically the issue of climate projections bias correction for hydrological modelling, by introducing a variation of the fully asynchronous calibration approach (in which hydrological models are calibrated directly with raw climate model outputs), whose main feature is constraining the calibration for each calendar month, rather than over the whole period.

15 The basic idea behind is conceptually simple, and the new approach is proposed as a “middle ground” between conventional methods based on climate output bias correction techniques and the fully asynchronous method. Results are interesting and deserve to contribute to the ongoing discussion on the addressed topic, but before publication, some major changes and/or clarifications are needed.

20 We sincerely thank the reviewer for the careful evaluation of our manuscript and for recognizing the relevance of our work in the context of hydrological projections under climate change. The reviewer provides several constructive comments and insightful suggestions that we believe will significantly improve the clarity, robustness and overall quality of the manuscript.

Below, we address each of the reviewer’s comments in detail and outline the corresponding revisions that we propose to make to the manuscript.

25 First of all, from a strictly mathematical point of view, a more detailed analysis is needed to examine the differences arising when using a single distribution rather than 12 distributions derived from the main distribution, highlighting their effects. This would strengthen the methodology significantly, along with other specific clarifications (e.g., why the calibration is constrained at a monthly scale rather than, e.g., seasonal or 15-day scales?).

30 We agree with the reviewer that this aspect was not sufficiently discussed in the original manuscript. The choice of a monthly temporal scale in the semi-asynchronous method aims to introduce temporal structure while preserving the core principle of the asynchronous framework, which relies on distribution-based calibration rather than exact temporal alignment.

The monthly scale represents a compromise between coarser (e.g., seasonal) and finer (e.g., 15-day) temporal aggregations. In this sense, moving from a single annual distribution to 12 monthly distributions enables a partial reintroduction of temporal information, while still avoiding full temporal synchronization.

35 In addition, monthly aggregation is commonly used in bias correction methods, including the conventional approach adopted in this study, ensuring methodological consistency across the compared frameworks.

We acknowledge that alternative temporal discretizations and weighting schemes could be considered. While a formal sensitivity analysis was beyond the scope of this study, we expect that the main conclusions would remain unchanged.

To address this comment, we will add a few sentences to section 2.3.4.

40 *“The monthly discretization was selected to capture key seasonal hydrological processes while maintaining enough data points within each subset for robust distribution estimation. Although other temporal aggregations (e.g., sub-monthly groupings) could be considered, they are not expected to alter the main conclusions of this study.”*

We will also add this sentence to the end of the discussion section to better reflect this point.

“In addition, exploring alternative temporal discretizations (e.g., sub-monthly groupings) represents a promising avenue for future work to further assess the sensitivity of the method to the chosen temporal structure.”

45 Then, calibrations based on RMSE (Eqs. 2 and 3) are more strongly driven by higher streamflow values than those based on KGE (Eq. 1). Therefore, the comparison between the three approaches is compromised by the use of two different objective functions. I suggest, for at least one catchment, using the same objective function (RMSE) in all cases and checking the changes and their extent.

50 The reviewer raises an important concern regarding the influence of the objective function on the comparison between methods. This point was also raised by the other reviewer. To address this, we recalibrated the conventional method for the Matane catchment using RMSE, in addition to the original calibration based on KGE. This ensures consistency with the objective functions used in the asynchronous and semi-asynchronous methods.

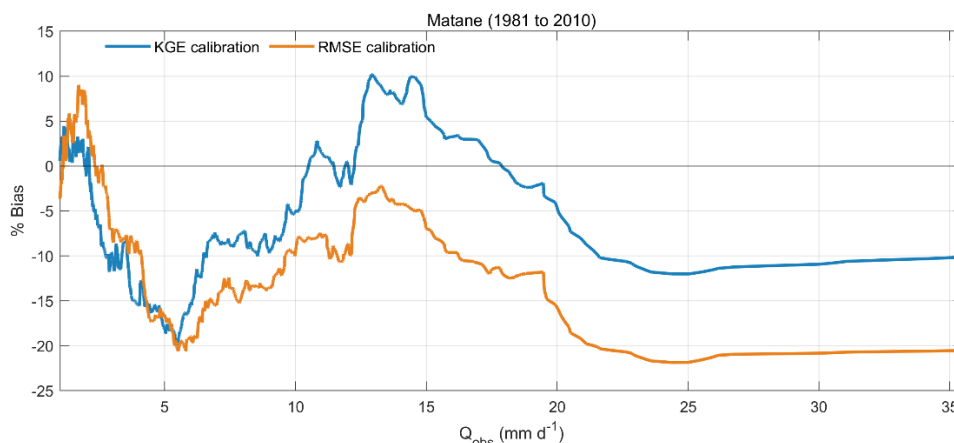
55 Figures 1 and 2 present the results obtained using both calibration strategies for the reference period (1981–2010). Figure 1 shows that calibrating with RMSE does not improve the bias in higher streamflow values observed with the conventional method. In fact, the RMSE-based calibration performs slightly worse than the KGE-based calibration in this regard.

As expected, each calibration performs better according to its own objective function (i.e., higher KGE for the KGE-based calibration and lower RMSE for the RMSE-based calibration). However, both approaches produce very similar simulated hydrographs and overall performance (Figure 2), indicating that the differences induced by the choice of objective function remain limited.

60 These results confirm that, while the choice of objective function introduces some level of uncertainty, it does not significantly affect the overall behaviour of the model or the conclusions of this study.

To address this point, we will add the following sentence to Section 4.2 and will add the two figures to the Appendix G:

65 *“In addition, the choice of objective function used during calibration of the conventional method represents another source of uncertainty. Nevertheless, sensitivity tests conducted on the Matane catchment showed that using RMSE instead of KGE for the conventional method leads to very similar results, indicating that this choice does not significantly influence the conclusions of the study (Appendix G).”*



70 **Figure 1. Performance comparison between the conventional method calibrated using RMSE and KGE for the Matane catchment during the reference period (1981–2010). The figure shows the percentage bias between observed and simulated streamflows obtained using meteorological observations.**

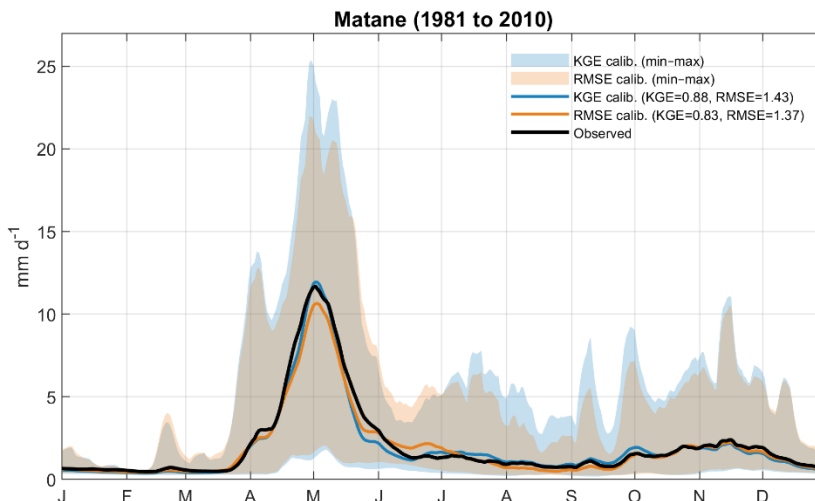


Figure 2. Seasonal streamflow comparison between the conventional method calibrated using RMSE and KGE and observed data across the Matane catchment.

Another question concerns the extent to which global climate model output can be used in the calibration of a hydrological model without prior bias correction. I mean, some global models, in some cases, perform so poorly locally that they do not even reproduce seasonal patterns (e.g., wet winters and dry summers, or vice versa). Is it correct to use raw data in these cases? Some restrictions should be considered and proposed for practical applications.

We agree with the reviewer that this is an important practical consideration. It is well known that some GCMs may exhibit substantial biases at the local scale, including an inadequate representation of seasonal patterns.

However, one of the key motivations behind asynchronous and semi-asynchronous approaches is precisely to avoid the limitations associated with bias correction. While bias correction can improve agreement with historical observations, it may also smooth extreme events, reduce inter-model variability, and introduce an additional source of uncertainty, as different correction methods can lead to divergent results.

In the asynchronous framework, calibration is performed directly on streamflow distributions generated from raw climate model outputs. In this context, model parameters implicitly compensate for biases in the climate inputs, effectively embedding a form of bias adjustment within the calibration process itself.

Applying bias correction prior to calibration would therefore remove one of the main advantages of these approaches and depart from the methodological framework proposed in previous studies (Ricard et al., 2019, 2020, 2023). Moreover, our results show that the projected relative changes in key hydroclimatic variables are consistent between the semi-asynchronous (without bias correction) and conventional (with bias correction) methods, suggesting that omitting bias correction does not significantly alter the study's conclusions, while improving the representation of extreme events.

That said, we acknowledge that the applicability of these methods may depend on the ability of GCMs to represent essential climatic features, such as seasonality. In practical applications, preliminary screening of climate models could be considered to exclude simulations that fail to reproduce key hydroclimatic patterns.

To address this point, we will add the following sentence to Section 4.2:

“In this study, climate model selection was not performed because the objective was not to develop a credibility-based climate change assessment, but rather to compare the behaviour of the three methods under a common ensemble spanning a wide range of biases. In practical applications, however, screening climate models based on their ability to reproduce key historical climatic features, such as seasonality, may help improve the reliability of hydrological simulations. More generally, when studies are intended to support climate change adaptation, selecting a more credible ensemble after historical evaluation of model performance may be preferable to using all models indiscriminately (Krysanova et al., 2018).”

Finally, two methodological choices should be better justified, even though I acknowledge they are not the main focus of the paper.

105 a) L135: the area covered by a single ERA5 cell is equal to $31 \times 31 = 961$ km², which is bigger than most of the selected catchments. The choice of referring to ERA5 rather than ERA5-Land is weak and partly unclear. Please consider testing at least one catchment with the finer ERA5-Land dataset.

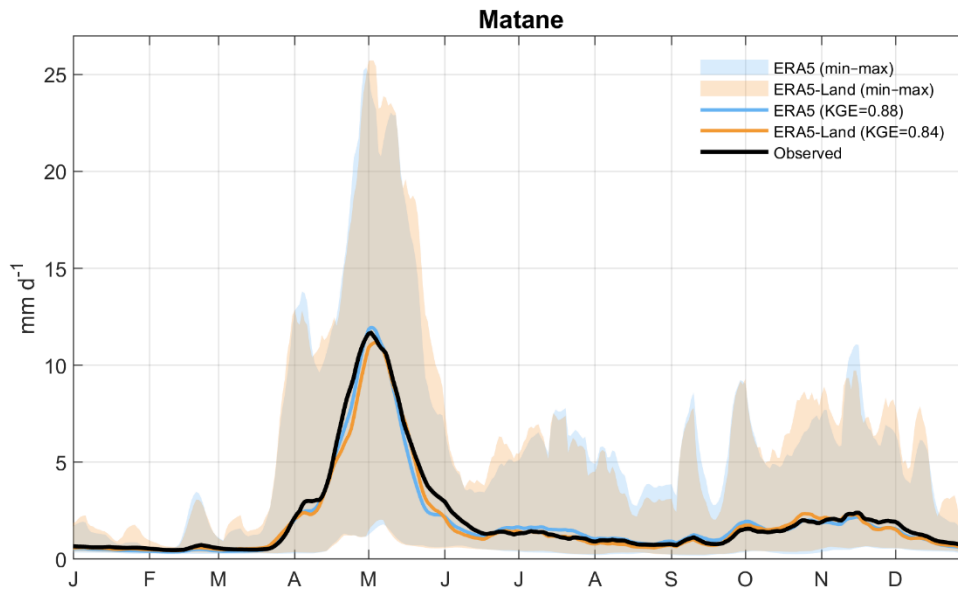
110 We acknowledge the reviewer's concern regarding the spatial resolution of ERA5 and the potential added value of ERA5-Land. While ERA5-Land offers a finer spatial resolution (~9 km), the focus of this study is on long-term (30-year) averages, which tend to smooth out spatial variability. In addition, the study area is non-mountainous and exhibits relatively limited spatial variability in meteorological conditions. Under these conditions, the added resolution of ERA5-Land is expected to have a limited impact on the hydrological simulations.

115 To further assess this point, we followed the reviewer's suggestion and recalibrated the Matane catchment using ERA5-Land data. Figure 3 presents the resulting simulations for the reference period (1981–2010), using both ERA5 and ERA5-Land along with their respective calibration parameters. The comparison shows very similar performance between the two datasets, indicating that the influence of the meteorological dataset on the simulated streamflow is limited in this case. Interestingly, ERA5 provides a slightly better KGE and a better representation of peak flows than ERA5-Land for this watershed, which further suggests that the finer spatial resolution of ERA5-Land does not necessarily translate into improved hydrological performance in this context.

120 These results support the use of ERA5 in this study and suggest that its impact on the overall conclusions is minimal, assuming that the Matane catchment is representative of the study area. We acknowledge, however, that ERA5-Land may be more relevant in regions with stronger spatial gradients (e.g., mountainous areas).

To address this point, we will add the following sentence to Section 4.2:

“A sensitivity test conducted on the Matane catchment using ERA5-Land showed very similar results, suggesting that the impact of this choice is limited in the context of this study.”



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Figure 3. Seasonal streamflow comparison between the conventional method calibrated using ERA5 and ERA5-Land and observed data across the Matane catchment.

b) LL182-185: Using IDW to downscale from more than 1° to 1000 m resolution is a very rough approach! Given the paper's main objective, less recent climate downscaling experiments, but at a higher resolution, would have been preferable.

130

We agree with the reviewer that the use of IDW to downscale coarse-resolution climate model outputs to a 1000 m grid is a relatively simple and approximate approach. However, the primary objective of this study is to compare hydrological modelling frameworks rather than to assess the impact of different downscaling techniques. To ensure a fair comparison between methods, it was essential to apply a consistent downscaling approach across all simulations.

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In addition, the analysis focuses on long-term (30-year) averages, which tend to reduce the influence of small-scale spatial variability introduced by the downscaling method. Under these conditions, the use of a more advanced downscaling technique is not expected to significantly alter the relative differences observed between the conventional, fully asynchronous and semi-asynchronous methods.

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Finally, introducing more complex statistical or dynamical downscaling methods would add an additional layer of uncertainty and methodological variability, potentially obscuring the interpretation of the differences between the hydrological modelling approaches. For these reasons, a simpler and consistent approach was preferred in the context of this comparative study.

Below, I add some other minor comments. I hope my review can help improve the robustness of the research and the quality of the manuscript.

L90: The concept that the asynchronous method can hinder the temporal coherence in hydrological processes should be better framed and contextualised. Is it only a problem concerning snow melting?

145 We agree that this point required clearer framing. The loss of temporal coherence in the fully asynchronous method is not limited to snowmelt processes, although it is particularly evident in snow-dominated catchments. More fundamentally, it stems from the calibration framework itself, which does not enforce any temporal alignment between simulated and observed conditions, as it relies on distribution-based metrics rather than time series comparison.

As a result, inconsistencies can arise in the timing of key processes, such as snow accumulation and melt and these mismatches
150 can propagate to other components of the hydrological cycle, including streamflow, evapotranspiration and groundwater recharge.

To address this, we will revise the sentence in the introduction (L90) to better contextualize the origin of this limitation and clarify that it affects multiple hydrological processes beyond snow dynamics.

L235: unclear. Why “raw data”? I understand the data were corrected using the MBC algorithm.

155 We agree that this statement was unclear. The term “raw data” was misleading in this context, as the hydrological model is calibrated using observed meteorological data, while the climate model outputs are bias corrected using the MBC algorithm. This will be clarified in the revised manuscript. We propose to replace this sentence:

“*Climate change studies were subsequently conducted using bias-corrected climate model data. Hydrological simulations were carried out for each climate model over both the reference and future periods, using a hydrological model calibrated
160 with raw data for each catchment.*”

With this sentence:

“*Climate change impact assessments were subsequently conducted using bias-corrected climate model data. Hydrological simulations were performed for each climate model over both the reference and future periods, using a hydrological model calibrated with observed meteorological data for each catchment.*”

165 LL289-290: That’s true, but, on the other hand, the computational cost of the bias correction should be accounted for. Please elaborate on that (maybe the best place is Section 4.2).

We agree that the computational cost associated with bias correction should be acknowledged. While the conventional method includes an additional bias correction step, its overall computational demand remains lower than that of the fully asynchronous and semi-asynchronous methods, as calibration is performed only once per catchment, rather than for each climate model.

170 To clarify this point, we will revise Section 4.2 to explicitly highlight this trade-off between bias correction costs and the significantly higher calibration cost required by the asynchronous and semi-asynchronous approaches. We propose to add this sentence to Section 4.2:

“Although the conventional method also involves an additional bias correction step, its overall computational demand remains lower, as calibration is performed only once per catchment.”

175 LL352-353: Please add units to numbers.

Units will be added to the revised manuscript.

LL399-426 and Tables D1-D3: Considering the absolute mean instead of the mean is incorrect. This way, the climate change signal cannot be properly understood. Furthermore, Figure 5 is not very clear in highlighting the different performances of the three methods, especially regarding projected changes, which, in my view, is the most important feature to assess (in other
180 words, how much do the different methods influence the projected climate change signal?).

We will clarify that the absolute mean bias was computed only for the reference period across the 10 catchments to assess how close each method is to observations. Using the mean bias for the reference period instead could lead to misleading interpretations, as positive and negative biases may cancel out across catchments, resulting in values close to zero despite substantial deviations at the individual catchment scale. The use of the absolute mean bias in this context was therefore intended
185 to better reflect the magnitude of model errors. Moreover, we replaced the mean by the median when summarizing results across catchments, as the median is less influenced by outliers (following RC2 comments).

However, we agree with the reviewer that using the absolute mean for projected changes is not appropriate, as it prevents a correct interpretation of the climate change signal. This will be corrected in Tables D1–D3, where median changes are will now be reported instead of absolute values for projected changes, and the associated text will be revised accordingly.

190 Regarding Figure 5, we acknowledge that the figure presents a large amount of information. Its objective is not primarily to quantify the climate change signal, but rather to provide a comparative overview of the behaviour of the three methods across multiple catchments, indicators and periods. Simplifying the figure (e.g., by reducing the number of indicators, periods, or catchments) would improve readability but would also limit its ability to convey this multidimensional comparison. To address this, we will add clarifying wording in the figure caption to guide the reader and explicitly refer to Appendix D for a more
195 detailed assessment.

Fig. 6 is not clear. The caption should explain the meanings of the terms in the legend.

We agree that the caption was not sufficiently clear. It will be revised to explicitly describe the meaning of the legend.

I suggest reversing the order of Appendices E and F, because Appendix F is mentioned first in the text (therefore, Appendix F should become Appendix E and vice versa). Anyway, the hydrographic network should also be shown alongside the DTM.

200 The order of Appendices E and F will be revised to ensure consistency with their first occurrence in the text. In addition, the hydrographic network will also be added alongside the DTM to improve the clarity and completeness of the figure.

Fig. 9 (and related text). Looking at Absolute Differences, it seems that the behaviours of Fully-Asynchronous and Conventional methods are much closer than Semi-Asynchronous and Fully-Asynchronous. Please provide more details about that.

205 We agree with the reviewer that this point required further clarification. Additional explanations will be added in the revised manuscript to better describe the similarities observed between the fully asynchronous and conventional methods, as well as the differences with the semi-asynchronous approach in terms of absolute changes of Figure 9.

LL628-635: not completely clear to me. Does the conventional method really produce an increased intermodal variability in the future? Is this a weakness of the conventional method? Why? And is this a problem for maintaining the ensemble's
210 diversity?

We agree that this point was not sufficiently clear in the original manuscript and appreciate the opportunity to clarify it. As shown in Figure 7, the conventional method exhibits relatively low inter-model variability during the reference period compared to the asynchronous and semi-asynchronous methods. This reduced variability is primarily due to the bias correction step, which constrains the climate model outputs toward the observed reference conditions and therefore tends to reduce
215 differences among models during the historical period.

In the future period, however, the inter-model variability of the conventional method increases and becomes comparable to that of the semi-asynchronous method for several variables, including streamflow, interflow, groundwater recharge, and snow water equivalent. This behaviour is mainly a consequence of the way the conventional framework is constructed. Bias correction tends to compress inter-model variability during the reference period so that the simulations fit the historical
220 reference more closely, but it does not constrain the magnitude or direction of future projected changes. As a result, the distinct signals carried by each climate model progressively re-emerge in the future period, and the effects of non-stationary biases can also contribute to increasing inter-model spread.

By contrast, the fully asynchronous method already shows relatively large inter-model variability during the reference period because it directly uses raw climate model inputs during calibration. This variability remains high in the future period, rather
225 than increasing substantially, because it is already embedded in the calibration framework from the start. The semi-asynchronous method shows an intermediate behaviour, with variability that remains more stable between periods.

This behaviour is therefore not necessarily a weakness of the conventional method, but rather a characteristic of how it processes climate data. It does not reduce ensemble diversity itself, but it changes how that diversity is distributed between the reference and future periods.

230 To improve clarity, this explanation will be explicitly incorporated into the revised manuscript, both in the description of Figure 7 and in Section 4.1.

LL691-699: This paragraph does not provide particularly novel information. I suggest removing it (or shortening it substantially) for conciseness.

The paragraph will be removed from the manuscript to improve conciseness.

235 LL732-737: This paragraph is a kind of repetition.

The paragraph will be removed from the manuscript to avoid redundancy.

Finally, I could not find some articles cited in the text in the reference section (Senatore et al., 2022; Chae and Chung, 2024). An overall check would be useful.

240 A thorough review of the references will be conducted, and the reference list will be updated accordingly in the revised manuscript.

We appreciate the reviewer's insightful comments, which will help improve the clarity and quality of the manuscript.

Sincerely,

Frédéric Talbot on behalf of all authors