Enhancing physically based and distributed hydrological model calibration through internal state variable constraints

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Editor's comments

Dear Authors

Three reviewers reviewed the adjusted manuscript and while the overall manuscript improvement improved there are some issues to be addressed. Two reviewers raised concern regarding the calibration / calibration strategy. Please clarify these points and/or discuss shortcomings of the approach in the discussion as I understand the point reviewer 2 raised.

Sincerely,

Albrecht Weerts

We thank the editor for summarizing the remaining concerns and for emphasizing the need for a fair comparison between GW and GW-RC. Both configurations share the same model structure, forcing, calibration parameters, number of evaluations, and algorithm. The only differences are the inclusion of the recharge term in GW-RC's objective function and the two-step calibration required to incorporate recharge constraints in the absence of high-resolution recharge observations.

We now explicitly acknowledge in Section 4.4 that this two-step procedure introduces a minor asymmetry, which may limit the extent to which the comparison is a fully controlled experiment. We also note that with improved recharge datasets, future work could implement a single-step calibration for both configurations.

These clarifications, along with the expanded discussion in Section 4.2 and the inclusion of the final calibrated parameter sets in Appendix D, directly address the methodological and transparency concerns raised by the reviewers.

Thank you for your review.

Sincerely,

Frédéric Talbot on behalf of all authors

Anonymous referee #1

I appreciate the clarification that the GW and GW-RC configurations share the same model complexity and differ only in calibration targets. However, my core concern remains: to rigorously isolate the effect of adding an internal state variable constraint (groundwater recharge), both configurations must be calibrated under truly identical condition, same model, data, and algorithm, except objective function for the presence or absence of the recharge term. Without this "apples-to-apples" setup, observed differences may reflect changes in calibration design rather than the actual benefit of the recharge constraint. Even small differences in objective functions or procedures can confound interpretation.

To assess causality in calibration and equifinality studies, it is essential to vary only one factor at a time. Hydrological modeling literature emphasizes designing controlled comparisons where only one factor (e.g. model structure or calibration strategy) is varied at a time (Clark et al., 2015). For example, Pool et al. (2025) calibrated the same model with discharge only, evapotranspiration only, and both together, explicitly isolating the effect of multi-variable calibration under identical setups. Similarly, calibrating GW and GW-RC with the same objective structure (except for the recharge term) would allow direct assessment of how internal constraints influence parameter identifiability and simulation realism.

We thank the reviewer for this comment and for highlighting the importance of ensuring a controlled comparison between configurations. In our study, configurations GW and GW-RC were explicitly designed to share the same model structure and complexity, with identical calibration parameters, number of evaluations, and calibration algorithm. The sole differences are in the objective function, where GW-RC includes groundwater recharge alongside streamflow, and in the parameter space during calibration. While it is not entirely clear which specific aspect of the methodology the reviewer is concerned about, we suspect it may relate to the two-step calibration approach applied in the GW-RC configuration.

For GW-RC, a two-step calibration was required to incorporate groundwater recharge. In the first step, regional recharge estimates derived from available large-scale data were used to constrain the range of five recharge-sensitive parameters. In the second step, the model was recalibrated using streamflow and the recharge standard deviation, allowing each catchment to freely adjust its recharge rates within the constrained parameter space. This approach allows the model to adapt recharge estimates to each catchment's specific conditions, preventing the regional estimates from exerting disproportionate influence on the final recharge outcomes. This two-step process is the only practical way to integrate recharge constraints in our study area without imposing unrealistic values. Conversely, configuration GW could not be calibrated with this two-step procedure, as it does not use recharge constraints.

We acknowledge that the optimal "apples-to-apples" setup described by the reviewer, where only the objective function differs, would require high-quality, high-resolution recharge observations to allow a single-step calibration. Such data are not available for our study region, and this limitation is common in many other regions where this type of methodology could be applied. In this context, the two-step procedure we propose represents a practical solution to address the absence of complete recharge observations. Regional recharge estimates can serve as an a priori constraint, which the model then optimizes based on streamflow data (and groundwater recharge standard deviation) at the catchment scale. Future work benefiting from improved recharge datasets could implement a single-step calibration using both streamflow and recharge, enabling a more direct comparison between configurations. To address this, we have added a few sentences in Section 4.4 explicitly acknowledging the limitation of our two-step approach and noting that future work with improved recharge observations could adopt a one-step calibration for a more direct comparison between configurations.

Here are the added sentences:

"The two-step calibration adopted for GW-RC, necessitated by the absence of high-quality, spatially distributed recharge observations, limits the extent to which a fully direct comparison with GW can be achieved. Future work with access to such datasets could implement a single-step calibration using both streamflow and recharge, enabling a more controlled assessment of the effects of internal recharge constraints."

Equifinality is central here: calibrating to streamflow alone often yields many parameter sets that produce similar outputs but divergent internal processes (Pool et al., 2025). Including internal data like recharge helps reduce equifinality by narrowing the feasible parameter space. Gallart et al. (2007) demonstrated this clearly showing that internal catchment observations reduced uncertainty in discharge and baseflow predictions. But for such added value to be credibly demonstrated, the comparison must be fair. Without symmetric calibration design (e.g., calibrating GW-RC using streamflow only as well), conclusions about the "effectiveness" of recharge constraints remain suggestive, not definitive.

We thank the reviewer for emphasizing the importance of equifinality in hydrological modeling and for noting that incorporating internal state variables like recharge can help reduce parameter uncertainty. In our study, configuration GW is identical to configuration GW-RC except for the inclusion of the recharge term in the objective function and the associated two-step procedure used to define the parameter space. Both configurations share the same model structure, complexity, calibration parameters, number of evaluations, and optimization algorithm. The only differences are those directly related to integrating groundwater recharge, which we have described in detail in our methodology.

The very purpose of GW-RC is to test the added value of including recharge information in calibration. Removing recharge from the objective function would negate the defining feature of this configuration and transform it into configuration GW. Instead, our approach uses GW as the "streamflow only" baseline and GW-RC as the "streamflow plus recharge" configuration, ensuring that the difference between them reflects the influence of recharge constraints.

We also recognize that the use of a two-step calibration in GW-RC, necessitated by the lack of high-resolution spatially distributed recharge observations, introduces a minor asymmetry in the calibration design. As noted in our revised manuscript, future work could address this by using high-quality recharge observations in a single-step calibration for both configurations, allowing an even more direct and controlled assessment of how recharge constraints influence equifinality and simulation realism.

In short, my call for a more controlled experiment is not about simplifying the setup, but enabling causal inference. Holding model structure and forcing constant while toggling the recharge constraint is the only way to quantify its true benefit or trade-off. Multi-objective calibration is praised for reducing equifinality, but its effectiveness must be benchmarked against an identical single-objective case. I strongly encourage the authors to consider recalibrating GW and GW-RC on commensurate terms to ensure that the observed improvements in GW-RC are truly attributable to internal constraints, and not to differences in calibration setup.

References

Clark, M. P., et al. (2015). A unified approach for process-based hydrologic modeling: 1. Modeling concept. Water Resources Research, 51(4), 2498–2514.

Pool, S., Fowler, K., Gardiya Weligamage, H., & Peel, M. (2025). Multivariate calibration can increase simulated discharge uncertainty and model equifinality. EGUsphere. https://doi.org/10.5194/egusphere-2025-1598

Gallart, F., Latron, J., Llorens, P., & Beven, K. (2007). Using internal catchment information to reduce the uncertainty of discharge and baseflow predictions. Advances in Water Resources, 30(4), 808–823.

We thank the reviewer for this valuable suggestion and for emphasizing the importance of causal inference in evaluating the benefits of recharge constraints. In our study, GW and GW-RC are identical in model structure, forcing, calibration parameters, number of evaluations, and optimization algorithm, with differences arising solely from the inclusion of the recharge term in the objective function and the two-step calibration process required to integrate it. We acknowledge that the most direct way to achieve a fully symmetric calibration design would be to recalibrate GW-RC using streamflow only. However, this would remove the defining characteristic of GW-RC and effectively reproduce the GW configuration. As discussed in our revised manuscript, the asymmetry introduced by the two-step calibration is an inherent consequence of working without high-resolution, spatially distributed recharge observations. Future work with such data could apply a single-step calibration to both configurations, enabling the perfectly controlled comparison the reviewer describes.

Thank you once again for your constructive review.

Sincerely,

Frédéric Talbot on behalf of all authors

Referee #2

Thank you for the thorough revisions and thoughtful responses to my comments. I appreciate the considerable effort the authors have put into improving the manuscript. The changes, particularly the enhanced abstract, more precise explanation of model configurations, expanded methodological details, and enhanced discussion on model performance and calibration strategy, have significantly strengthened the clarity and scientific value of the work.

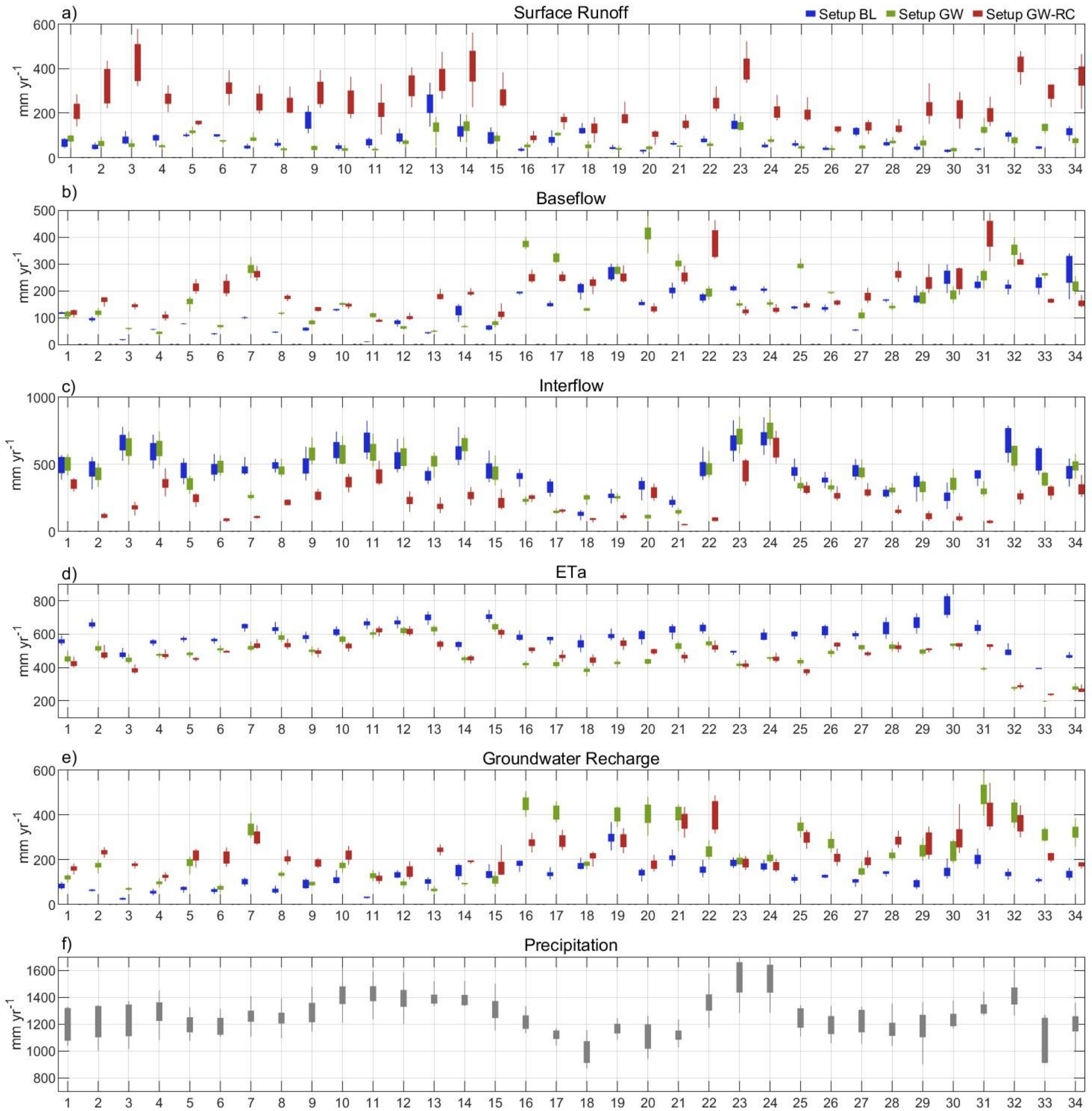
I wish the authors all the best in their future scientific endeavours.

I would like to make one final optional minor suggestion regarding Figure 5. Since precipitation is the same across all model setups, it may be visually more apparent to display only a single box per catchment for precipitation—perhaps using a neutral colour like black—rather than repeating it for each configuration. This adjustment would reduce visual redundancy and help emphasise the differences between model outputs, and water balance closure.

Thank you again for addressing the comments so carefully.

Sincerely,

We thank the reviewer for the thoughtful and encouraging feedback, as well as for the valuable suggestion regarding Figure 5. We agree that displaying a single precipitation box per catchment using a neutral colour improves the visual clarity of the figure and better highlights the differences among model outputs and water balance closure. Figure 5 has been revised accordingly. Here is the new Figure 5:



Thank you once again for your constructive review and supportive comments.

Sincerely,

Frédéric Talbot on behalf of all authors

Anonymous referee #3

The manuscript addresses a significant issue in hydrological modeling, specifically focusing on the calibration of distributed, physically based models by integrating groundwater recharge constraints. The authors demonstrate how incorporating additional calibration constraints beyond streamflow can enhance internal process representations despite minor trade-offs in conventional performance metrics. This study presents valuable insights into the implications of equifinality in hydrological modeling and the benefits of multi-objective calibration approaches.

The authors have adequately addressed the comments raised by the previous three reviewers, resulting in a manuscript with a strong organization and clear presentation. However, I identify one major issue that requires further clarification from the authors: In Section 2.3.2, the authors state that a total of 17 parameters were calibrated in this study. It remains unclear whether all 17 parameters were re-calibrated independently for each configuration (BL, GW, GW-RC), or if some parameters were held constant while only a subset was re-calibrated.

We thank the reviewer for the thoughtful and encouraging comments, as well as for highlighting the need for clarification regarding the calibration process. All 17 parameters were recalibrated independently for each configuration (BL, GW, GW-RC), with no parameters held constant between configurations. We agree that this point could be made clearer in the manuscript and have added the following sentence to Section 2.3.2:

"For each model configuration (BL, GW, GW-RC), the full set of 17 parameters was recalibrated independently within the specified ranges."

If all 17 parameters were recalibrated independently for each configuration, the authors should further discuss the implications of incorporating groundwater recharge constraints on the entire parameter set. Specifically, do the groundwater recharge constraints influence parameter values even in seemingly unrelated sub-models, such as those controlling snowmelt and evapotranspiration processes?

If only a subset of parameters were re-calibrated and the remaining parameters were kept fixed across configurations, the authors should explicitly specify which parameters were held constant and clearly justify their rationale for this choice.

We thank the reviewer for the insightful question regarding the broader influence of incorporating groundwater recharge constraints on the full parameter set. All 17 calibration parameters were recalibrated independently for each configuration. While Section 4.2 already discusses the effects of recharge constraints on key parameters such as *QDsnow* and drainage density, we agree that the implications for other parameters warrant further discussion. To address this, we have added the following paragraph at the end of Section 4.2:

"Moreover, configuration GW-RC also exhibited lower values of k_h (storage coefficient for interflow), higher values of Krec (recession constant for hydraulic conductivity), lower correction factors for PET in summer, and higher correction factors for PET in winter compared to the other two configurations. These differences indicate that adding groundwater recharge constraints during calibration can influence parameter values in sub-models that are seemingly unrelated to groundwater processes, such as evapotranspiration. This suggests that the recharge constraint propagates through the model structure,

affecting multiple hydrological components. A complete list of calibrated parameter values for each catchment and configuration is provided in Appendix D."

Additionally, I suggest that the authors include a supplementary document listing the final calibrated parameter sets for all catchments across each configuration. This would allow readers to intuitively compare parameter differences between configurations, facilitating greater understanding and reproducibility of the results.

This is an excellent suggestion. In response, we have included a new table in Appendix D presenting the final calibrated parameter values for all catchments across each configuration (BL, GW, GW-RC). This addition enables readers to directly compare parameter values between configurations.

A.

Catchment		k_D			k_H			d_r			QD_{Snow}			c_0			K_{rec}			T_0			$T_{R/S}$			C_{WH}		
Code	**Name**	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	Bonaventure	24.7	24.7	25.0	25.0	24.8	24.5	38	46	19	0.1	0.1	0.4	1.8	2.2	2.6	0.5	0.1	0.9	-0.6	-0.1	0.4	0.3	0.5	0.0	0.1	0.1	0.1
2	York	25.0	24.8	24.7	24.1	24.3	14.9	38	18	5	0.1	0.1	0.8	1.2	1.8	1.4	0.6	0.4	0.3	-1.3	-0.2	0.3	1.3	0.2	1.6	0.1	0.1	0.1
3	Dartmouth	21.6	24.4	24.7	20.9	17.7	1.8	49	50	8	0.1	0.1	0.8	2.1	2.1	2.1	0.8	0.9	0.2	-0.3	-0.1	0.1	1.4	1.0	2.3	0.1	0.1	0.2
4	Matane	24.7	24.9	24.6	25.0	24.7	19.8	44	48	20	0.1	0.1	0.6	2.3	2.9	2.5	0.1	0.2	0.2	-0.1	0.6	0.6	1.8	0.7	1.1	0.1	0.1	0.1
5	Rimouski	24.8	24.9	24.6	24.9	25.0	23.8	43	17	4	0.2	0.3	0.4	1.5	1.9	2.1	0.2	0.2	0.9	-0.1	0.6	-0.3	0.3	-2.4	2.5	0.2	0.2	0.2
6	Des Trois-Pistoles	24.7	24.7	25.0	24.9	24.5	1.6	49	48	2	0.2	0.2	0.8	1.9	2.8	2.1	1.0	1.0	0.5	0.2	1.0	0.7	-3.1	-2.6	-2.3	0.3	0.2	0.2
7	Du Loup	24.7	23.4	24.9	24.3	24.1	16.8	41	8	4	0.1	0.2	0.6	2.0	2.6	1.9	0.2	0.2	0.9	-0.8	0.7	0.6	1.7	0.3	-2.6	0.2	0.3	0.3
8	Ouelle	24.7	24.9	24.6	24.6	23.6	3.5	40	50	19	0.1	0.1	0.6	2.3	2.5	2.3	0.1	0.1	1.0	-0.1	0.0	0.6	1.7	1.8	1.2	0.3	0.3	0.3
9	Famine	22.6	24.5	25.0	19.8	11.8	1.6	46	48	18	0.1	0.1	0.7	1.9	2.7	2.6	1.0	0.7	0.3	-1.1	-0.8	0.7	1.1	1.2	0.3	0.2	0.3	0.2
10	Bécancour	24.9	24.4	24.7	23.6	25.0	23.5	35	47	20	0.1	0.1	0.7	2.7	2.5	2.0	0.1	0.9	0.9	0.2	0.2	0.0	1.3	1.3	1.7	0.1	0.1	0.2
11	Nicolet Sud-Ouest	25.0	24.1	24.9	24.9	24.7	16.4	49	36	33	0.1	0.1	0.7	2.9	2.8	2.5	0.6	1.0	0.9	0.7	0.5	0.8	-3.0	-0.2	-2.9	0.1	0.2	0.2
12	Nicolet	24.9	24.7	24.8	22.8	19.1	5.0	25	45	28	0.1	0.2	1.0	3.0	2.0	1.7	0.9	0.9	1.0	0.7	-0.6	0.3	-2.9	0.2	0.0	0.1	0.2	0.2
13	Eaton	24.7	24.3	20.9	3.5	2.9	2.0	20	49	9	0.3	0.4	1.0	2.8	3.0	1.8	0.9	0.9	0.2	0.0	-0.1	-0.2	-3.6	-0.3	-3.8	0.1	0.2	0.1
14	Au Saumon	25.0	24.7	24.9	20.6	12.7	2.7	49	49	18	0.1	0.3	1.0	2.5	3.0	2.1	0.9	1.0	0.2	-0.8	0.0	0.1	1.7	-2.6	-1.5	0.1	0.1	0.1
15	Noire	25.0	24.5	24.9	13.8	14.9	2.5	27	45	21	0.1	0.3	1.0	2.1	3.0	2.2	0.8	0.8	1.0	-1.0	0.3	0.3	0.5	-1.2	0.4	0.3	0.3	0.2
16	Rouge	17.8	23.5	24.3	24.8	24.7	24.8	40	5	6	0.1	0.1	0.3	0.8	1.7	0.9	0.1	0.9	0.2	-2.3	-0.8	-3.2	0.1	0.7	1.9	0.1	0.2	0.3
17	Gatineau	24.1	22.6	24.9	12.7	24.3	24.8	19	5	6	0.3	0.3	0.6	0.9	1.7	0.9	0.3	0.2	0.7	-3.0	-0.1	0.0	3.1	-3.8	-1.9	0.3	0.3	0.2
18	Kinojévis	24.9	22.9	24.0	24.4	24.2	21.4	46	19	7	0.5	0.1	0.5	1.1	1.8	0.9	0.8	0.3	0.8	0.9	0.5	-1.9	-3.2	-0.9	3.5	0.3	0.1	0.2
19	Mattawin	22.6	24.1	24.7	24.8	24.9	20.9	25	15	4	0.1	0.1	0.6	1.7	2.2	0.8	0.1	0.1	0.6	-0.3	1.0	-1.3	0.8	-1.7	1.3	0.2	0.1	0.2
20	Croche	9.3	11.1	24.8	21.6	13.7	24.8	25	1	17	0.1	0.1	0.4	0.8	2.2	1.0	0.3	0.3	0.2	-1.2	1.3	-0.2	-0.5	-2.2	-3.2	0.3	0.2	0.2
21	Vermillon	12.7	12.2	24.7	20.1	21.5	23.9	12	5	1	0.2	0.1	0.5	1.0	1.9	1.2	0.3	0.3	0.3	-0.5	0.5	0.5	-3.2	0.9	0.7	0.3	0.2	0.1
22	Batiscan	22.6	22.5	24.9	24.5	24.8	1.8	18	25	1	0.2	0.1	0.8	0.7	0.5	0.7	0.2	0.2	0.6	-1.9	-2.1	0.2	-1.8	-3.0	-1.7	0.2	0.3	0.2
23	Sainte-Anne	24.9	24.2	24.9	23.6	18.5	7.3	34	25	23	0.3	0.3	0.8	1.7	1.4	1.0	0.2	0.3	0.9	0.3	0.0	-0.1	-3.2	-0.2	-0.4	0.1	0.1	0.1
24	Bras du Nord	24.7	24.9	25.0	24.4	24.3	24.2	34	46	22	0.1	0.1	0.4	1.4	1.0	1.3	0.7	0.2	0.7	0.4	-1.5	0.3	-3.4	-1.2	-0.7	0.1	0.2	0.1
25	Ouareau	21.8	23.0	24.7	24.8	16.3	24.7	39	7	12	0.2	0.1	0.5	1.6	2.5	1.6	0.1	0.1	0.6	0.5	0.8	0.7	-1.2	0.5	-1.9	0.2	0.2	0.1
26	L'Assomption	24.7	22.5	24.8	24.3	24.5	25.0	33	31	13	0.1	0.1	0.4	1.1	2.3	1.6	0.1	0.1	0.7	-0.8	0.3	0.7	0.8	-1.0	-0.2	0.1	0.1	0.2
27	De l'Achigan	24.9	23.6	24.6	24.7	1.6	6.0	44	48	11	0.1	0.1	0.4	2.2	2.8	2.7	0.2	0.6	0.8	0.3	0.6	0.6	-2.8	-0.2	-2.1	0.1	0.2	0.2
28	Du Loup	24.9	23.4	24.5	24.9	24.7	24.3	19	19	3	0.2	0.1	0.4	1.0	1.3	1.6	0.4	0.2	0.1	-0.8	0.6	0.3	0.0	-0.4	2.8	0.2	0.2	0.2
29	Petit Saguenay	24.9	24.6	24.8	24.8	3.6	2.7	22	9	2	0.1	0.2	0.7	1.5	1.8	1.0	0.1	0.3	0.9	0.2	0.0	-0.1	0.3	-3.8	1.3	0.1	0.2	0.2
30	Petite rivière Péribonca	24.7	24.3	24.8	23.6	24.4	1.2	40	26	4	0.1	0.1	0.8	1.7	0.7	0.5	0.3	0.3	0.7	1.5	-3.5	-0.8	-3.1	2.4	0.2	0.1	0.3	0.3
31	Métabetchouane	24.2	24.8	25.0	24.4	18.0	16.5	26	9	1	0.1	0.2	0.5	0.6	1.4	1.1	0.1	0.1	0.5	-2.2	-1.1	1.3	-0.4	-0.8	-2.5	0.3	0.3	0.2
32	Valin	25.0	22.8	25.0	23.5	19.4	17.2	44	10	7	0.2	0.1	0.9	1.2	2.4	0.8	0.1	0.5	0.9	0.7	1.4	0.4	-2.5	1.2	0.3	0.1	0.1	0.2
33	Sainte-Marguerite Nord-Est	25.0	24.7	24.6	24.3	17.5	18.2	39	11	12	0.1	0.3	0.9	1.7	2.4	1.3	0.1	0.3	0.9	0.6	1.1	0.7	-2.6	-3.5	-0.9	0.1	0.1	0.1
34	Godbout	24.8	23.2	24.8	23.8	24.7	24.6	44	21	20	0.3	0.1	0.9	1.3	2.4	1.4	1.0	0.3	0.6	0.1	0.6	0.5	0.7	1.0	-1.8	0.2	0.2	0.1
	Average	**23.4**	**23.3**	**24.6**	**22.6**	**19.9**	**14.6**	**35**	**28**	**12**	**0.2**	**0.2**	**0.7**	**1.7**	**2.1**	**1.6**	**0.4**	**0.4**	**0.6**	**-0.4**	**0.0**	**0.1**	**-0.6**	**-0.5**	**-0.2**	**0.2**	**0.2**	**0.2**

B.

Catchment		C_{rfr}			$f_{i,summer}$			$f_{i,fall}$			$f_{i,winter}$			$f_{i,spring}$			Kol			K_{XY}			d_z		
Code	**Name**	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	Bonaventure	0.7	0.2	0.7	1.3	1.1	1.0	0.5	0.2	0.6	0.5	2.0	1.5	1.4	0.8	0.7	-	83	9	-	3.2	1.4	1.1	1.3	1.4
2	York	0.6	0.6	0.8	1.7	1.1	0.5	1.0	0.6	0.2	0.2	0.2	1.3	1.6	1.4	1.8	-	5	15	-	0.6	1.5	1.1	1.3	1.4
3	Dartmouth	0.6	0.9	0.8	1.2	1.2	0.9	1.4	0.7	0.7	0.3	0.2	0.9	0.6	0.7	0.6	-	35	55	-	0.2	1.7	0.9	1.0	1.3
4	Matane	0.6	0.6	0.9	1.2	1.6	1.3	1.7	0.8	0.9	0.4	1.0	1.0	0.9	0.2	0.5	-	97	44	-	3.2	1.6	1.1	1.1	0.9
5	Rimouski	0.6	0.6	0.7	1.2	1.2	0.9	1.7	0.8	0.7	0.3	0.8	0.2	0.9	0.7	1.1	-	23	35	-	0.3	0.5	1.1	1.1	0.8
6	Des Trois-Pistoles	0.7	0.4	0.4	1.3	1.3	1.2	1.2	1.5	1.1	0.1	0.3	0.6	1.0	0.6	0.7	-	44	56	-	1.5	2.4	1.4	0.8	0.8
7	Du Loup	0.7	1.0	0.7	1.8	1.2	1.1	1.4	0.6	0.8	0.4	0.1	0.8	0.8	1.1	1.0	-	20	41	-	0.2	2.3	1.1	1.3	1.2
8	Ouelle	0.7	0.8	1.0	1.1	1.1	1.1	2.0	1.5	1.0	0.7	1.0	1.2	1.1	0.9	0.9	-	40	92	-	0.2	2.2	1.1	1.0	1.2
9	Famine	0.6	0.7	0.7	1.0	1.4	1.0	1.7	0.1	0.8	0.2	0.5	0.9	1.1	0.7	0.7	-	21	63	-	0.2	0.6	1.2	0.9	1.1
10	Bécancour	0.6	1.0	0.6	1.5	1.3	1.2	0.6	1.5	0.7	0.7	0.7	1.4	0.9	0.7	0.5	-	47	75	-	1.4	3.6	1.1	1.4	1.3
11	Nicolet Sud-Ouest	0.7	0.3	0.9	1.2	1.4	1.2	1.0	0.5	0.9	0.8	0.6	1.1	1.1	0.9	0.9	-	62	97	-	0.2	0.6	1.1	1.0	0.9
12	Nicolet	0.8	1.0	0.8	1.2	1.7	1.7	1.0	0.6	0.4	0.9	0.2	1.3	1.0	0.9	0.6	-	65	62	-	0.2	3.9	1.3	0.8	1.1
13	Eaton	0.6	0.8	0.9	0.9	1.2	0.8	1.2	1.4	1.3	0.8	0.4	1.1	1.6	1.0	0.9	-	21	37	-	0.2	2.8	1.2	0.8	1.2
14	Au Saumon	0.8	0.9	0.9	1.0	1.1	0.9	1.3	0.7	0.7	0.9	0.1	0.9	0.7	0.6	0.6	-	20	66	-	0.2	3.9	1.3	0.8	1.2
15	Noire	0.8	0.7	0.7	1.2	1.2	1.0	1.1	1.5	1.6	0.6	0.2	0.7	1.2	1.0	0.9	-	64	94	-	0.3	2.6	1.2	0.8	1.1
16	Rouge	1.0	0.9	1.0	1.2	1.1	1.7	0.9	0.9	0.6	1.5	0.3	1.7	1.0	0.5	0.2	-	16	25	-	2.2	2.6	1.2	1.3	0.9
17	Gatineau	0.6	0.8	0.8	1.3	1.2	0.8	0.4	0.5	1.2	1.9	0.1	1.3	1.1	0.6	0.9	-	15	14	-	2.2	4.0	1.0	1.3	1.1
18	Kinojévis	0.7	0.5	0.5	0.4	1.0	0.7	1.2	1.0	1.8	1.0	0.9	1.3	1.7	0.2	0.6	-	4	21	-	3.2	3.9	1.4	1.1	1.2
19	Mattawin	0.6	0.7	0.4	1.2	0.6	0.9	1.4	1.3	1.7	0.4	0.3	1.7	1.1	1.0	0.8	-	14	21	-	3.0	3.8	1.4	1.4	1.2
20	Croche	0.6	0.7	1.0	1.7	1.2	1.0	1.3	0.2	1.6	1.4	0.1	1.3	0.6	0.8	0.7	-	26	29	-	0.8	3.6	0.9	0.8	1.1
21	Vermillon	0.7	0.5	0.7	1.9	1.4	1.0	0.5	1.0	2.0	0.5	0.3	2.0	1.0	0.9	0.2	-	4	21	-	1.0	4.0	1.3	1.3	1.1
22	Batiscan	0.7	0.7	0.7	1.6	1.2	0.4	1.4	0.7	1.4	0.2	0.5	1.9	1.0	1.2	1.3	-	21	32	-	4.0	3.5	1.1	1.3	1.0
23	Sainte-Anne	0.7	0.8	0.9	1.1	1.0	0.9	0.6	0.3	0.6	0.4	0.6	1.6	1.0	0.8	0.6	-	7	40	-	1.3	2.9	1.2	1.1	1.2
24	Bras du Nord	0.8	0.8	0.8	1.5	1.2	0.9	1.0	0.5	0.5	0.7	0.2	1.9	1.0	0.9	0.7	-	3	33	-	1.7	3.1	0.8	1.3	0.9
25	Ouareau	0.6	0.9	0.8	1.4	1.0	1.0	1.8	0.6	0.7	1.5	0.5	1.0	0.5	0.7	0.1	-	26	29	-	1.0	3.9	0.9	1.1	1.2
26	L'Assomption	0.8	0.8	0.3	1.6	1.3	1.3	0.6	0.7	1.3	0.4	0.7	1.3	1.3	0.6	0.5	-	9	12	-	1.2	3.2	1.3	1.4	1.2
27	De l'Achigan	0.7	0.7	0.7	1.2	1.3	1.4	0.6	0.4	0.4	0.7	0.9	0.6	0.9	0.5	0.4	-	34	32	-	0.4	1.2	1.1	1.1	0.8
28	Du Loup	0.9	0.6	1.0	1.6	1.2	1.2	1.0	0.8	0.4	0.4	0.5	1.5	1.4	0.9	0.8	-	4	16	-	4.0	2.6	1.1	1.2	1.0
29	Petit Saguenay	0.7	0.1	0.3	1.7	1.4	0.6	1.9	0.9	1.2	0.5	0.3	1.3	1.3	0.8	1.5	-	25	46	-	1.8	1.8	1.1	1.3	1.2
30	Petite rivière Péribonca	1.0	1.0	0.4	1.7	1.1	0.4	1.9	0.8	1.6	0.3	1.7	2.0	1.9	0.9	1.5	-	6	35	-	3.7	4.0	1.3	1.1	1.3
31	Métabetchouane	0.7	0.9	0.7	1.5	1.2	0.7	1.0	1.2	1.7	1.2	0.4	1.6	1.2	0.2	1.2	-	3	28	-	3.2	3.8	1.1	1.2	1.0
32	Valin	0.6	0.7	0.8	1.4	0.7	0.1	0.2	0.7	0.3	0.3	0.2	0.7	0.9	0.4	1.2	-	12	77	-	2.2	3.9	1.1	1.1	1.2
33	Sainte-Marguerite Nord-Est	0.7	0.8	0.4	0.9	0.6	0.1	0.4	0.3	0.6	0.1	0.2	1.0	0.9	0.3	0.8	-	27	80	-	1.3	2.8	1.1	1.3	1.2
34	Godbout	0.7	0.6	0.9	1.0	0.7	0.2	0.8	0.5	0.9	0.3	1.2	1.5	1.4	0.3	0.7	-	5	34	-	2.5	3.3	1.4	1.2	1.2
	Average	**0.7**	**0.7**	**0.7**	**1.3**	**1.2**	**0.9**	**1.1**	**0.8**	**1.0**	**0.6**	**0.5**	**1.2**	**1.1**	**0.7**	**0.8**	**-**	**27**	**43**	**-**	**1.5**	**2.7**	**1.1**	**1.1**	**1.1**

Figure D1. Final calibrated parameter values for all catchments across each model configuration (BL, GW, GW-RC).

We appreciate your constructive feedback and the time you have dedicated to reviewing our work. Sincerely,

Frédéric Talbot on behalf of all authors