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On optimization of calibrations of a distributed hydrological model with spatially distributed information on snow

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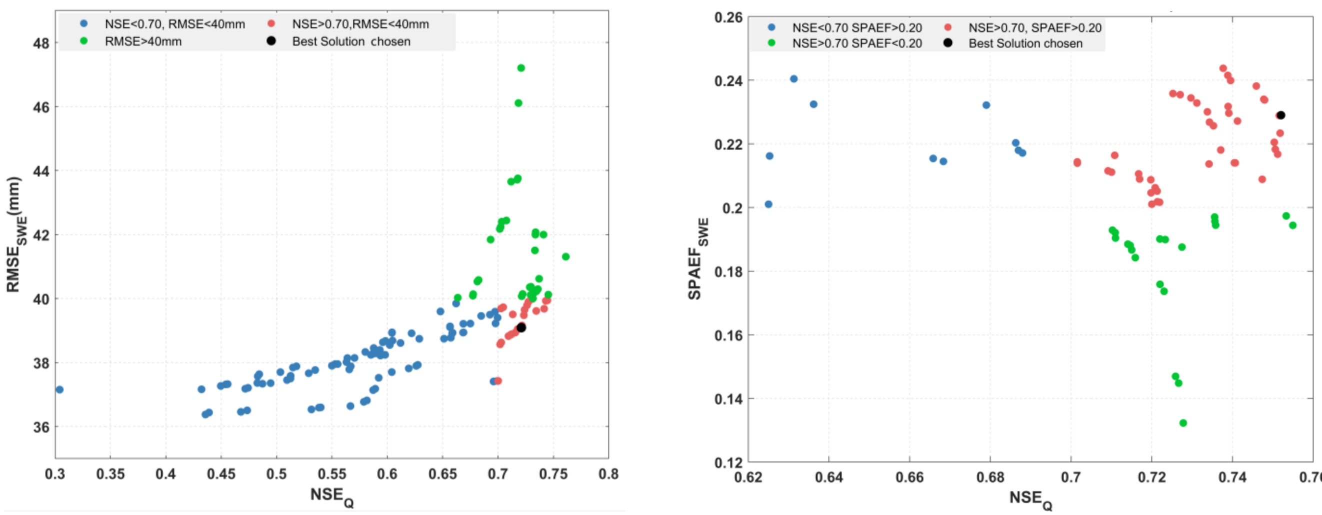
Analysis of Pareto-Trade off:

In hydrology, the Pareto-Archived trade-off refers to the balance between different conflicting objectives that need to be considered when calibrating a hydrological model. Pareto-Archived is an evolutionary algorithm used for multi-objective optimization. The algorithm archives non-dominated solutions found during the optimization process. Non-dominated solutions are those that cannot be improved in one objective without degrading performance in another. By retaining this diverse set of non-dominated solutions over successive generations, the algorithm ensures a robust representation of the Pareto front, which comprises the optimal trade-offs between the conflicting objectives. This representation is valuable as it offers a range of practicable solutions to choose from, each corresponding to different trade-offs. Moreover, the presence of the Pareto archive prevents the algorithm from prematurely converging to a single solution, allowing it to explore a broader region of the search space and discover a more comprehensive set of optimal solutions, ultimately enhancing the efficiency and effectiveness of the optimization process.

NSE is maximized for streamflow hereafter called NSE_Q and RMSE is minimized for snow water equivalent (SWE), hereafter called $RMSE_{SWE.}$ SPAEF is maximized for SWE hereafter called $SPAEF_{SWE}$. In Figure S1, the Pareto fronts between objective functions NSE_Q and $RMSE_{SWE}$ as well as NSE_Q and $SPAEF_{SWE}$ are presented. During calibration with PADDS, different combination of optimized objective function is generated. Out of these combinations the best one is selected as the optimum solution for the calibration experiment. A total of 11 parameters are calibrated (Table S1).

Table S1 Parameters and their boundary values for the calibration

Parameter Name	Lower Bound	Upper Bound
P-1. Base refreezing temperature (mm/d)	-3	2
P-2. Temperature threshold for melt - Coniferous (°C)	-4	4
P-3. Temperature threshold for melt - Deciduous (°C)	-4	4
P-4. Temperature threshold for melt - Open (°C)	-4	4
P-5. Melt factor for coniferous forests (mm/d per °C)	2	15
P-6. Melt factor for deciduous forests (mm/d per °C)	2	15
P-7. Melt factor for open areas (mm/d per °C)	2	15
P-8. Multiplication factor for PET	0.7	1.5
P-9. Depth of the first soil layer (m.)	0.01	0.2
P-10. Depth of the second soil layer (m.)	0.1	1.5
P-11. Depth of the third soil layer (m.)	1	7



(a) **(b)**

Figure S1 : (a) PADDS trade-off for NSE_Q vs. $RMSE_{SWE}$, (b) PADDS trade-off for NSE_Q vs. $SPAEF_{SWE}$

In each multiobjective calibration a total of 1000 simulations are done out of which the best 10% solutions are used for trade-off analysis. In Figure S1 (a), the Pareto front is partitioned into three distinct clusters (blue, green and red) based on the application of an NSE_Q threshold value set at 0.70 and an $RMSE_{SWE}$ threshold value set at 40 mm. These thresholds serve to characterize the behaviour of the hydrological model. Figure S2 complements the analysis by presenting the parameter distributions for each cluster during the Pareto trade-off. The blue cluster is where "NSE_Q<0.70, $RMSE_{SWE}$<40mm", the green cluster is where "$RMSE_{SWE}$>40mm" and the red cluster is where "NSE_Q >0.70, $RMSE_{SWE}$ <40mm". Therefore, the red cluster comprise all the solution where both the objective functions are optimal (NSE_Q maximised and $RMSE_{SWE}$ minimized). Similarly, in Figure S1 (b), a visual representation of the Pareto front is presented by using three distinct colours (blue, green and red) to denote different zones. This trade-off is based on the NSE_Q threshold value set at 0.70 and the $SPAEF_{SWE}$ threshold value set at 0.20. The optimal solution can be identified within the red zone, where both objective functions, NSE_Q and $SPAEF_{SWE}$ are maximized. Figure S3 complements the analysis by presenting the parameter distributions for each cluster during the Pareto trade-off between NSE_Q and $SPAEF_{SWE}$.

In Figure S2, parameters, P1, P5 and P11 demonstrate significant influence on the trade-off. This suggests that variations in these parameters have a substantial impact to accurately replicate both streamflow and SWE data simultaneously. Parameter P6, representing the Melt Factor for Deciduous Forests, shows a close association with the objective function $RMSE_{SWE}$ that can affect the model's performance with respect to SWE, which is crucial for capturing the variability of snowpack. The calibrated parameters, P3, P4, P8, and P10 show a stronger inclination towards NSE_Q during the calibration process. This implies that variations in these parameters has a more noticeable impact on NSE_Q compared to $RMSE_{SWE.}$ It is visible in Figure S2, that certain parameters display limited sensitivity to the trade-off between NSE_Q and $RMSE_{SWE}$. For instance, P2, P7 and P9 demonstrated relatively little influence on the trade-off. This imply that variations in these parameters might have less impact on the overall performance of the model when considering NSE_Q and $RMSE_{SWE}$ together.

In Figure S3, we investigate the behaviour of each of the 11 selected calibration parameters during the Pareto trade-off. The analysis reveals a distinct trade-off between NSE_Q and $SPAEF_{SWE}$ in the case of P6, suggesting that small adjustments to this parameter can significantly impact the model's performance with respect to both objective functions. For other parameters, we observed distinct patterns. P10 demonstrates a close association with NSE_Q, indicating its influence. On the other hand, parameters such as P1, P2, P4, P5, and P8 are closely related to $SPAEF_{SWE}$, suggesting their substantial impact on this objective. The behaviour of these parameters is crucial in optimizing the $SPAEF_{SWE}$ objective function. Certain parameters, P3, P7, P9, and P11, appear to have little influence on the trade-off.

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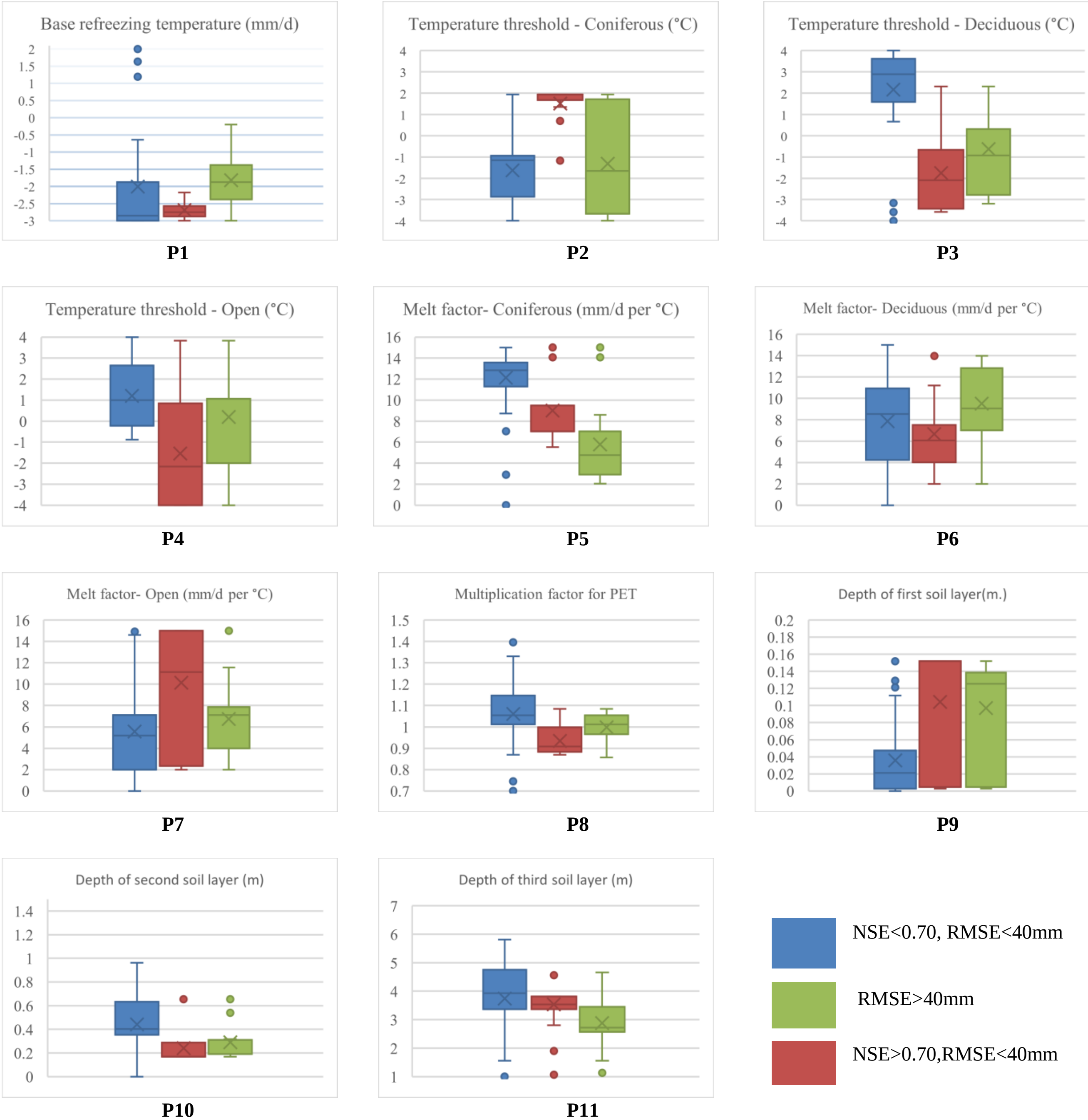

Figure S2 Different parameter values for trade-off between NSE_Q and $RMSE_{SWE}$

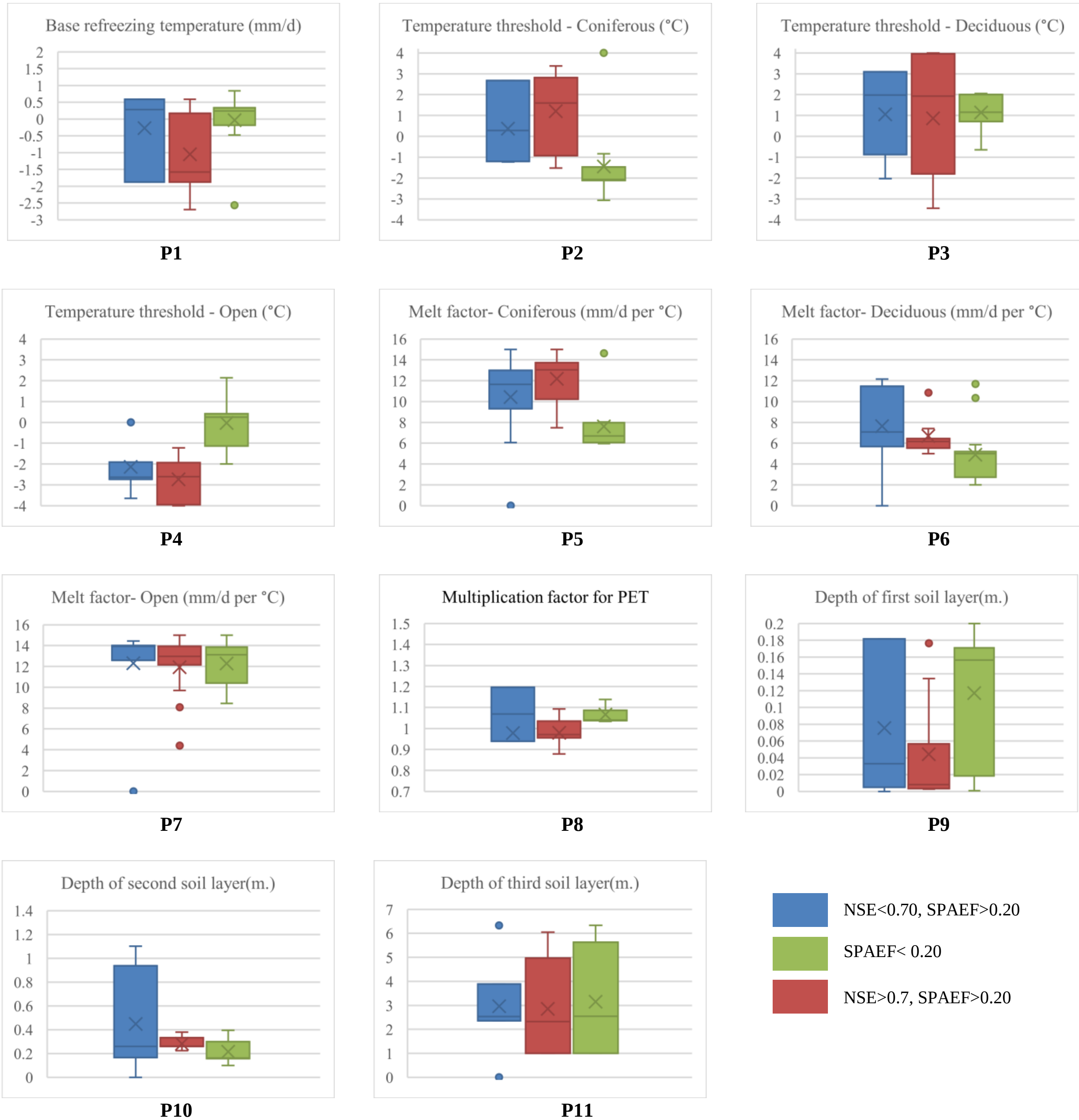

Figure S3 Different parameter values for trade-off between NSE_Q and $SPAEF_{SWE}$

Table S2 below shows additional analyses performed using data from January and February, and the results demonstrated that SPAEF performs well with data from both these months.

Table S2 SPAEF calibration with respect to March, February and January

Calibration				
Parameters	**NSE**	**SPAEF_March & NSE**	**SPAEF_Feb & NSE**	**SPAEF_Jan & NSE**
1. Base refreezing temperature (mm/d)	-1.049	-1.879	-0.661	-1.432
2. Temperature threshold for melt Coniferous (°C)	0.827	3.374	0.830	3.194
3. Temperature threshold for melt Deciduous (°C)	0.241	-1.797	3.941	3.923
4. Temperature threshold for melt Open (°C)	-1.280	-2.224	-0.715	-2.040
5. Melt factor for coniferous forests (mm/d per °C)	13.591	13.732	9.261	14.681
6. Melt factor for deciduous forests (mm/d per °C)	3.913	11.465	1.980	1.998
7. Melt factor for open areas (mm/d per °C)	9.841	13.395	14.430	8.410
8. Multiplication factor for PET	1.031	1.039*	0.958*	1.133*
9. Depth of the first soil layer (m.)	0.003	0.003*	0.100*	0.022*
10. Depth of the second soil layer (m.)	0.501	0.339*	0.199*	0.146*
11. Depth of the third soil layer (m.)	2.095	1.000*	2.175*	1.000*
Average SWE in corresponding month of SPAEF calibration		135.49	116.24	67.35
NSE	**0.762**	**0.737**	**0.739**	**0.733**
KGE	**0.776**	**0.764**	**0.771**	**0.840**
RMSE Spatial(mm)	**45.35**	**39.38**	**51.90**	**50.23**
SPAEF wrt SNODAS Jan	**-0.027**	**0.01**	**0.077**	**0.101**
SPAEF wrt SNODAS Feb	**0.157**	**0.157**	**0.201**	**0.181**
SPAEF wrt SNODAS March	**0.192**	**0.232**	**0.197**	**0.167**
Validation				
NSE	**0.735**	**0.747**	**0.770**	**0.756**
KGE	**0.757**	**0.789**	**0.803**	**0.838**