CALIBRATION AND VALIDATION OF A CONCEPTUAL HYDROLOGICAL MODEL IN SWAMPY RIVER BASINS OF LATVIA

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Abstract
In this study, the conceptual rainfall-runoff model METQ2007BDOPT was evaluated through detailed calibration and validation procedures carried out in five Latvian river basins, each characterised by diverse natural, topographical, and climatic conditions, including notably swampy areas with complex hydrological dynamics. Long-term observational runoff data covering a fifty-year period (1956–2006) were rigorously utilised to assess the model's overall performance and robustness. Satisfactory to good agreement was achieved between observed and simulated daily discharges across all tested basins, with correlation coefficients (r) ranging from 0.77 to 0.88 and determination coefficients (R^2) varying from 0.60 to 0.78, indicating reliable predictive capabilities. The strongest performance was recorded for the Malta River at Viļāni, reflecting highly consistent simulations of runoff patterns, whereas comparatively weaker but still acceptable results were observed for the Malmuta River at Kažava, likely due to more intricate swamp hydrology. These findings clearly confirm that the METQ2007BDOPT model can be effectively applied under varied environmental and hydrological conditions, particularly demonstrating its strength and adaptability in swamp-dominated river basins. Special emphasis was placed on refining key swamp-specific parameters within the model structure, effectively representing subtle yet crucial hydrological processes often overlooked or inadequately represented in conventional hydrological models. Such focused refinement enhances the model's precision and practical utility for hydrological forecasting and water resource management in complex landscapes.
Keywords: rainfall-runoff modelling, calibration and validation, swamp hydrology.

Introduction

Hydrological modelling is widely recognised as essential for understanding and managing water resources in regions characterised by complex hydrological dynamics, such as swampy river basins (Guo et al., 2017). These basins are defined by the presence of extensive wetlands, floodplains, and intricate interactions between surface water and groundwater (Spence et al., 2011). The accurate modelling of hydrological processes in these environments is considered crucial for applications such as flood risk assessment, water resource management, and ecosystem conservation (Merz et al., 2011).

The hydrological modelling of swampy river basins is associated with significant challenges, which are attributed to their unique and complex characteristics. These include notable spatial and temporal variability, limited data availability, and intricate hydrological interactions. Processes such as surface water-groundwater exchanges, evapotranspiration, and water storage dynamics exhibit high variability, complicating their representation within models (Koçyiğit et al., 2017). Additionally, the availability and quality of essential hydrological data, such as streamflow, groundwater levels, and precipitation, are often restricted, further impeding the calibration and validation of models (Vervoort et al., 2014). The representation of wetlands and floodplains also presents difficulties, as these features display non-linear and dynamic behaviour that is challenging to incorporate into hydrological frameworks (Spence et al., 2011). Furthermore, the complexity of these basins contributes to high levels of uncertainty and equifinality, where multiple parameter sets yield similar outputs, thereby complicating model reliability and interpretability (Alwan et al., 2016).

To address the unique challenges posed by swampy river basins, various approaches to hydrological modelling have been developed. Integrated surface water-groundwater models, such as MIKE SHE and ParFlow, are frequently employed to capture the interactions characteristic of these environments (Thirel et al., 2015). Wetland-specific models, including the Wetland Water Budget Model (WWBM) and the Wetland Hydrological Model (WHM), have been designed to represent the distinct hydrological processes within wetland ecosystems more effectively (Spence et al., 2011). Distributed hydrological models, such as the Soil and Water Assessment Tool (SWAT) and the Hydrological Simulation Program-FORTRAN (HSPF), are utilised to account for the spatial variability of hydrological processes across swampy regions (Zhang et al., 2013). The integration of remote sensing data, such as satellite imagery and soil moisture observations, with hydrological models has been demonstrated to improve the representation of these processes, particularly in data-scarce areas (Renard et al., 2010). In addition, uncertainty, and sensitivity analyses, including Monte Carlo simulations and Bayesian inference, have been applied to quantify and reduce the uncertainty associated with modelling these systems (Yin et al., 2016). Collectively, these approaches have been shown to enhance the accuracy and reliability of hydrological models in swampy river basins.

Earlier applications of METQ and its variants (e.g., METQ2007BDOPT) in Latvian basins have demonstrated overall effectiveness in simulating discharge under varying conditions, including forested and agricultural landscapes (Ziverts & Jauja, 1999; Bakute et al., 2015; Grinfelde & Bakute, 2017). However, swamp-dominated basins present unique difficulties owing to prolonged wetness, variable soil moisture regimes, shallow groundwater tables, and intricate groundwater-surface water exchanges. These conditions necessitate parameterisation that differs substantially from that used in more conventional terrains.

The aim of this study is to assess the performance of the METQ2007BDOPT model, with a specific emphasis on its application in swampy areas. By calibrating and validating the model in five Latvian river basins, this research seeks to evaluate its ability to simulate daily discharges under complex hydrological conditions characteristic of swampy environments. Additionally, the study aims to identify the model's strengths and limitations and propose enhancements to improve its effectiveness in representing the unique dynamics of swamp-dominated basins.

Materials and Methods

Study area and data

Five river basins - Imula, Iecava, Pērse, Malta, and Malmuta - were selected to represent a broad range of hydrological and geographical conditions, including swampy areas (Table 1). These basins exhibit varying levels of forest cover, agricultural activity, and topographical features, thereby providing a suitable test of the model's performance across multiple environmental settings.

The swampy nature of certain basins, particularly Malmuta and Malta, introduces added complexity. High forest coverage (e.g., Pērse basin, 47%) and flat, low-lying areas (e.g., Malmuta basin) influence runoff patterns and water storage. Long-term runoff data (1956–2006) were used for calibration and validation. Local meteorological records complemented these hydrological datasets.

Methods

The METQ2007BDOPT model employed in this study is a conceptual rainfall-runoff framework designed to simulate daily river discharges by incorporating key hydrological processes such as precipitation, evapotranspiration, and soil moisture dynamics. The calibration procedure aimed to align model parameters with observed discharges, while validation was undertaken using independent datasets to ensure that the model could reliably predict runoff patterns without overfitting to the calibration period.

Table 1

Characteristics of the studied river basins and hydrological stations

River	***Hydrological Observation Station***	***Catchment Area (km²)***	***Avg. Annual Precip. (mm)***	***Calibration Period***	***Validation Period***
Imula	Pilskalni	263	650–700	1956–1990	1991–1994
Iecava	Dupši	1166	650–730	1956–1990	1991–1994
Pērse	Usiņi	329	680–800	1956–1990	2001–2006
Malta	Viļāni	876	650	1976–1990	1991–1994
Malmuta	Kažava	192	650	1980–2000	2001–2006

Detailed basin-specific parameters were applied, particularly for the Malta and Malmuta basins, to capture the unique hydrological characteristics of swampy regions (Table 2). The key model parameters basically are the same as in the METQ98 (Ziverts & Jauja,1999). These parameters enhanced the model's capacity to simulate processes such as groundwater-surface water interactions, soil moisture variability, and snowmelt dynamics. Regarding Imula, Iecava and Pērse, we did not allocate swamp basin-specific parameters. Special consideration was given to swamp-related parameters, ensuring that the patterns of water storage and release in poorly drained soils were accurately represented. These parameters were calibrated to reflect distinct soil, groundwater, and climatic conditions.

Calibration focused on adjusting parameters to minimise discrepancies between observed and simulated discharges, thereby improving the model's accuracy 'Figure 1'. To maintain objectivity, non-overlapping calibration and validation periods were used. Performance was evaluated using statistical metrics, including correlation coefficients (r) and determination coefficients (R^2). The correlation coefficient assessed the linear relationship between observed and simulated values, while R^2 quantified the proportion of variance in observed discharges explained by the model.

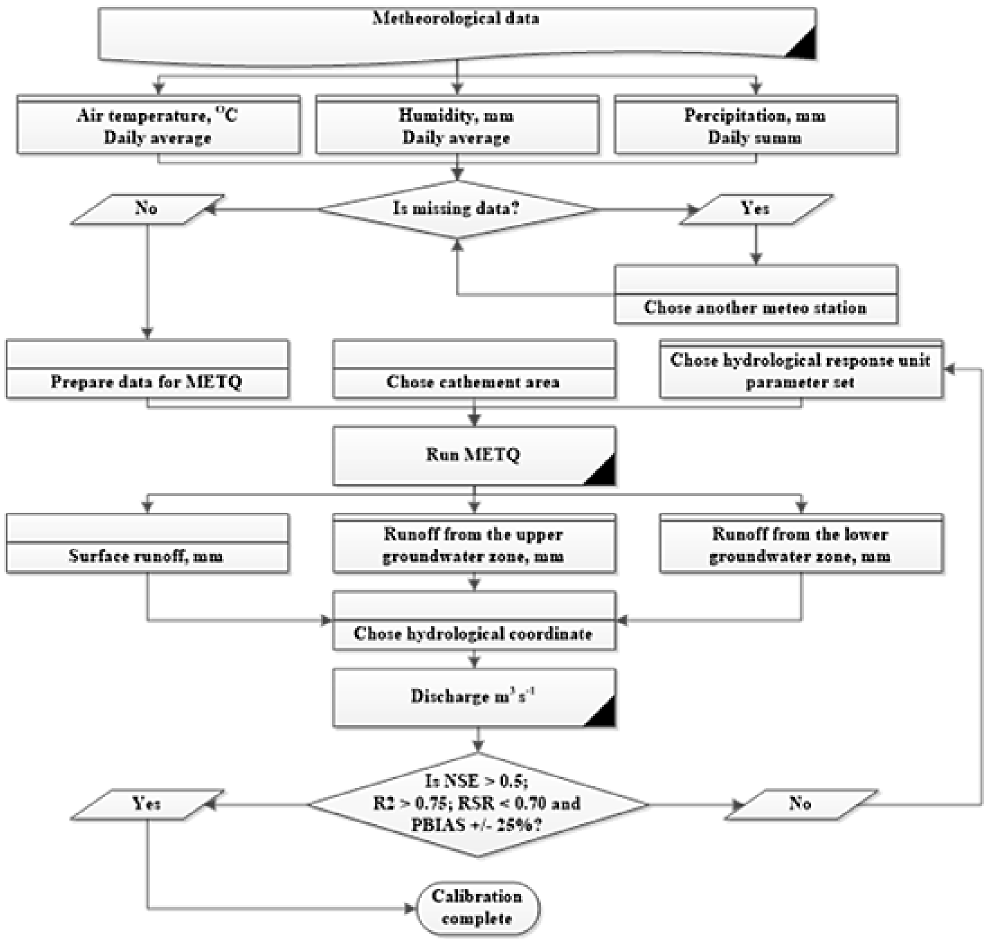
Table 2

Key model parameters for Malta and Malmuta Basins

Parameter	***Malta***	***Malmuta***
WMAX (mm)	30	20
ALFA	0.124	0.2
ZCAP (cm)	130	80
CMELT (mm/day)	3	2.5
PZ (cm)	305	60
RCHR	48	25
AMELTK	0.05	0.07

Attention was given to basin-specific parameters that allowed for the improved representation of swamp-influenced runoff processes, especially in the Malta and Malmuta basins. Parameters such as ZCAP, RCHR, and CMELT were critical for capturing soil moisture retention, groundwater recharge, and snowmelt dynamics, respectively. These parameters enabled the model to better account for hydrological complexities often associated with swampy and low-lying regions.

Figure 1
Calibration steps of the model METQ for the hydrological response unit



The study examined multiple river basins with varying climatic and physiographic conditions. Calibration and validation periods were determined by data availability: Malta (1976–1994), Pērse (1956–2006), Iecava (1956–1994), Malmuta (1980–2006), and Imula (1956–1994). This multi-basin approach ensured that the model could be tested under a range of conditions and that its performance could be more comprehensively evaluated.

Addressing the challenges inherent in swamp modelling required a careful approach. High spatial variability in swamp hydrology was tackled by using high-resolution precipitation and topographical data, allowing for a more accurate representation of localised swamp processes. The study did not employ proxy or remote sensing data (such as satellite-derived rainfall estimates) to compensate for sparse monitoring networks, focusing instead on refining the model's inherent process representations. Efforts were made to incorporate feedback mechanisms characteristic of swamp ecosystems, including prolonged surface water retention in depressional areas and gradual groundwater release. These processes, which have often been neglected or underrepresented in previous modelling attempts, were integrated to improve the reliability of the METQ2007BDOPT model's simulations, particularly in environments shaped by complex swamp hydrology.

Results and Discussion

The performance of the METQ2007BDOPT model was evaluated during both calibration and validation phases across all five basins (Table 3). The results indicated variable performance, reflecting the influence of basin-specific characteristics and swampy conditions. For the Imula Basin, moderate performance was achieved during calibration (R^2 = 0.66), whereas validation results showed weaker explanatory power (R^2 = 0.43). The correlation coefficient (r) during calibration (0.77) suggested a strong linear relationship between observed and simulated discharges, which declined somewhat during validation (r = 0.70), indicating a reduced yet still acceptable linear relationship.

Similarly, the Iecava Basin exhibited moderate calibration performance (R^2 = 0.66), followed by a diminished fit during validation (R^2 = 0.44). Although the R^2 value declined, the correlation coefficient (r) remained relatively robust, decreasing only slightly from 0.82 to 0.79. This finding suggests that while the proportion of explained variance was reduced, the overall linear association between observed and simulated values remained comparatively strong.

In contrast, the Pērse Basin performed well under both calibration (R^2 = 0.65) and validation (R^2 = 0.68) conditions. The correlation coefficient (r = 0.85) was consistently strong across both periods, indicating stable and reliable simulations of daily discharge. This stability implies that the model's parameterisation was particularly suitable for the Pērse Basin's hydrological characteristics.

Table 3
Calibration and validation performance of the METQ2007BDOP model

River Basin (Station)	***Calibration R²***	***Calibration r***	***Validation R²***	***Validation r***
Imula–Pilskalni	0.66	0.77	0.43	0.70
Iecava–Dupši	0.66	0.82	0.44	0.79
Pērse–Ūsiņi	0.65	0.85	0.68	0.85
Malta–Viļāni	0.78	0.88	0.69	0.87
Malmuta–Kažava	0.52	0.65	0.60	0.78

Among the studied basins, the Malta Basin at Viļāni achieved the highest overall performance. An excellent calibration fit was indicated by R^2 = 0.78, while a strong validation result of R^2 = 0.69 confirmed the model's robustness. Correlation coefficients remained high (r = 0.88 during calibration, r = 0.87 during validation), marking the Malta Basin as the benchmark for model adaptability and precision, as reflected in the performance metrics (Table 3).

The Malmuta Basin presented the greatest challenges. Although calibration performance was comparatively weak (R^2 = 0.52), a slight improvement during validation (R^2 = 0.60) suggested that the model's predictive capability increased over time. The correlation coefficient improved from 0.65 to 0.78, indicating that while initial parameterisation may not have been fully optimised for swampy conditions, certain aspects of the model configuration proved more effective under validation (Table 3).

Overall, the Malta Basin consistently outperformed the others, reflecting the model's adaptability to its specific hydrological conditions, whereas the Malmuta Basin posed significant challenges, highlighting the need for further refinement in swampy and low-lying terrains. Stable performance was demonstrated in the Pērse Basin, suggesting a strong suitability of the model's parameterisation for its environmental setting. Validation metrics generally showed slight declines or maintained consistency relative to calibration, indicating that while the model exhibited a robust predictive capacity, further enhancements could be implemented to improve accuracy and applicability across all studied basins.

The METQ2007BDOPT model has been demonstrated to perform strongly in simulating discharge patterns in swampy and variable basins, achieving high correlation coefficients (r = 0.77–0.88) (Guo et al., 2017). This indicates that the complex hydrological dynamics observed in these environments have been accurately replicated. The incorporation of swamp-specific parameters has been identified as a key factor in enhancing the model's capacity to represent these intricate systems (Guo et al., 2017).

Parameters such as WMAX, ZCAP, and RCHR have been found to play a critical role in capturing essential hydrological processes within swampy basins, including soil water storage, capillary rise, and groundwater recharge (Guo et al., 2017). Through the accurate representation of these processes, biases have been reduced, and the simulated runoff dynamics have been brought closer to the observed data (Guo et al., 2017). The importance of incorporating appropriate parameters and process representations when modelling hydrological systems with significant wetland and floodplain components is thereby highlighted.

The careful calibration of snowmelt parameters (CMELT and AMELTK) has further improved the model's capacity to depict seasonal transitions, particularly during periods when frozen conditions give way to thawed states (Guo et al., 2017). This has been deemed essential in Northern European climates, where snowmelt processes exert a critical influence on the overall hydrological regime (Guo et al., 2017).

The model's strong performance in swampy and variable basins has been attributed to its ability to capture the complex interactions between surface water, groundwater, and snowmelt processes (Guo et al., 2017). This contrasts with many traditional hydrological models, which often struggle to represent the unique characteristics of these environments with sufficient accuracy (Spence et al., 2011). Hydrological modelling includes various challenges, e.g., setting appropriate geomorphic boundary conditions, account for river channel dynamics, etc. (Swinnen et al., 2021). In addition, there does not exist a one-size-fits-all model, and it is important to improve performance of hydrological models (Mozafari et al., 2023).

The findings of this study underscore the importance of developing and applying specialised hydrological modelling approaches that are tailored to the specific challenges posed by swampy river basins (Merz et al., 2011). By incorporating appropriate parameters and process representations, researchers and water resource managers are better equipped to improve the understanding and management of these complex and ecologically significant systems (Koçyiğit et al., 2017).

Future research is recommended to continue exploring advanced hydrological modelling techniques, such as integrated surface water-groundwater models, wetland-specific modelling approaches, and the integration of remote sensing data, in order to further enhance the ability to simulate and predict the behaviour of swampy river basins (Vervoort et al., 2014). In addition, rigorous uncertainty analysis and sensitivity analysis techniques are necessary to quantify and mitigate the uncertainties inherent in hydrological modelling of such complex environments (Alwan et al., 2016).

When compared to other conceptual rainfall-runoff models, the METQ2007BDOPT framework has demonstrated strong competitiveness, particularly in swampy environments (Thirel et al., 2015). This can be attributed to the model's adaptability, which is underpinned by its basin-specific parameterisation (Thirel et al., 2015). Such a robust foundation provides opportunities for future refinements and broader applications to a wider range of catchment types (Thirel et al., 2015).

The reliability of the model in accurately simulating discharge patterns within swampy basins suggests that it can be effectively utilised for a variety of critical applications, including climate change scenario assessments, sustainable water resource planning, and integrated catchment management strategies (Thirel et al., 2015).

The insights derived from this study are expected to contribute to the development of improved modelling frameworks capable of better accommodating the complexities of wetland and swamp systems (Thirel et al., 2015). By advancing the understanding of critical hydrological processes in these environments, researchers and water resource managers will be better positioned to make more resilient and sustainable decisions regarding water resource management.

Conclusions

1. Through calibration and validation conducted across five Latvian river basins, the suitability of the METQ2007BDOPT model under swampy and variable conditions was confirmed. Robust results at Malta–Viļāni ($R^2 = 0.69$, $r = 0.87$) demonstrated the model's capability, while challenges at Malmuta–Kažava highlighted areas for improvement.
2. Incorporating basin-specific parameters significantly enhanced the model's capacity to capture the unique hydrological dynamics of swamp-dominated basins. Future efforts should focus on refining parameter estimation techniques, integrating finer-resolution data, and considering additional hydrological processes, such as biogeochemical cycles and vegetation-hydrology feedbacks,to produce even more accurate and ecologically relevant simulations.

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References

Alwan, N., Esmaeili, H., & Krupp, F. (2016). Molecular phylogeny and zoogeography of the capoeta damascina species complex (pisces: teleostei: cyprinidae). *Plos One, 11*(6), Article e0156434. https://doi.org/10.1371/journal.pone.0156434

Bakute, A., Grinfelde, I. & Lagzdiņš, A. (2017). Application of the model METQ for hydrological calculations. *Research for Rural Development,* 1, 139–144. https://doi.org/10.22616/rrd.23.2017.023

Grinfelde, I. & Bakute, A. (2017). Urban hydrological response unit parameter calibration and verification for conceptual hydrological model METQ. *Engineering for Rural Development,* 16, 1117-1122. https://doi.org/10.22616/ERDev2017.16.N236

Guo, D., Westra, S., & Maier, H. (2017). Impact of evapotranspiration process representation on runoff projections from conceptual rainfall-runoff models. *Water Resources Research, 53*(1), 435-454. https://doi.org/10.1002/2016wr019627

Koçyiğit, M., Akay, H., & Yanmaz, A. (2017). Estimation of hydrologic parameters of kocanaz watershed by a hydrologic model. *International Journal of Engineering & Applied Sciences, 9*(4), 42-50. https://doi.org/10.24107/ijeas.342039

Merz, R., Parajka, J., & Blöschl, G. (2011). Time stability of catchment model parameters: implications for climate impact analyses. *Water Resources Research, 47*(2). https://doi.org/10.1029/2010wr009505

Merz, R., Parajka, J., & Blöschl, G. (2011). Time stability of catchment model parameters: implications for climate impact analyses. *Water Resources Research*, *47*(2). https://doi.org/10.1029/2010wr009505

Mozafari, B., Bruen, M., Donohue, S., Renou-Wilson, F., & O'Loughlin, F., (2023). Peatland dynamics: A review of process-based models and approaches. *Science of the Total Environment*, 877, Article 162890. https://www.sciencedirect.com/science/article/pii/S0048969723015061

Renard, B., Kavetski, D., Kuczera, G., Thyer, M., & Franks, S. (2010). Understanding predictive uncertainty in hydrologic modeling: the challenge of identifying input and structural errors. *Water Resources Research*, *46*(5). https://doi.org/10.1029/2009wr008328

Spence, C., Guan, X., & Phillips, R. (2011). The hydrological functions of a boreal wetland. *Wetlands*, *31*(1), 75-85. https://doi.org/10.1007/s13157-010-0123-x

Swinnen, W., Broothaerts, N., & Verstraeten, G. (2021). Modelling long-term alluvial-peatland dynamics in temperate river floodplains. *Biogeosciences*, 18, 6181-6212. https://bg.copernicus.org/articles/18/6181/2021/

Thirel, G., Andréassian, V., Perrin, C., Audouy, J., Berthet, L., Edwards, P., …, & Vaze, J. (2015). Hydrology under change: an evaluation protocol to investigate how hydrological models deal with changing catchments. *Hydrological Sciences Journal*, *60*(7-8), 1184-1199. https://doi.org/10.1080/02626667.2014.967248

Vervoort, W., Miechels, S., Ogtrop, F., & Guillaume, J. (2014). Remotely sensed evapotranspiration to calibrate a lumped conceptual model: pitfalls and opportunities. *Journal of Hydrology*, 519, 3223-3236. https://doi.org/10.1016/j.jhydrol.2014.10.034

Yin, J., Yu, D., Yin, Z., Lü, M., & He, Q. (2016). Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of shanghai, china. *Journal of Hydrology*, 537, 138-145. https://doi.org/10.1016/j.jhydrol.2016.03.037

Zhang, H., Wang, Y., Li, D., & Wang, X. (2013). The effect of watershed scale on hec-hms calibrated parameters: a case study in the clear creek watershed in Iowa, us. *Hydrology and Earth System Sciences*, *17*(7), 2735-2745. https://doi.org/10.5194/hess-17-2735-2013

Ziverts, A. & Jauja, I. (1999). Mathematical model of hydrological processes METQ98 and its applications. *Nordic Hydrology*, *30*(2), 109-128. https://doi.org/10.2166/nh.1999.0006