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Executive summary of the dissertation thesis

Integration of satellite-derived soil moisture data in the hydrological model for prediction improvements of discharges and soil moisture

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Abstract

This thesis explores how additional data representing soil moisture can improve the calibration process of the hydrological rainfall-runoff model TUW in dual version and how it behaves when additional data is added to the model. Model calibration was performed on a mountainous catchment in Slovakia- Váh-Liptovský Mikuláš. Calibration of the model was performed from 2007 to 2014, and the validation was performed from 2015 to 2019. The dual version of the TUW model was run in a daily time step. In this study, different calibration scenarios were designed, branching the calibration process into temporal and spatial components. This study's novelty lies in running the TUW model calibration process in a dual version when the catchment is divided into distinctive land cover zones. Results show that multi-objective calibration, as opposed to single-objective calibration, achieves better results in general.

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1. Introduction

This thesis has several elements from which the main goals and directions of this work are derived. It aims to provide a novelty in research of using satellite-derived soil moisture data while incorporated in rainfall-runoff modelling as an additional input element. Moreover, this thesis aims to show the best practices of using a two-fold strategy in a catchment division for more precise results regarding discharge and soil moisture predictions. Research in hydrological modelling in different elevations and land divisions throughout the selected catchment in Slovakia are providing insight into the various hydrological behaviours and are critical elements for choosing one of the two offered strategies further in practice.

2. Goals of the thesis

In the following sections, the hypothesis of the PhD thesis are listed. These hypothesis should illuminate the pathways for improving the model's internal processes when additional information is involved. The hypotheses are set as follows:

- Explore how additional soil moisture data improves internal processes, including model calibration.
- Create different calibration scenarios and divide them into spatial components (different land cover zones across catchment) and temporal components (calibration periods).
- Choose a season in which an assumption is made about the fact that additional information, particularly soil moisture, would improve the overall performance of the model and its internal processes.
- The creation of the calibration strategy which involves different calibration approaches that consider different runoff and soil moisture weights.
- Performing different stages of model validation:

- Validation of the results in a period different from the calibration period on the same catchment.
- Validation of the internal processes of the model as the model simulates different components. Consideration of the internal structure of the model and verification of the model's physical functioning. After incorporating all calibration scenarios, verification of how the model takes components into account.
- Validation of achieved results by transferring calibration parameters from the primary catchment onto neighbouring, ungauged catchment and comparing parameters response to a similar environment.

3. Methods

The chosen methodology aligns with the main aims and hypothesis of the study, which include running the rainfall-runoff model - TUW model in dual mode, performing calibration and validation processes in a mountainous catchment in Slovakia, performing multi-objective calibration of the model using soil moisture data as an additional component, and validating gained results in an ungauged catchment in Slovakia.

The dual version of the TUW model was developed from the original TUW model, and this version was used in the study. This variant represents a lumped dual-layer hydrological model developed at the Vienna University of Technology for academic purposes (Parajka, 2009). TUW model dual is a conceptual rainfall-runoff model with a dual representation of the soil layer. Soil layers are represented by the skin soil layer, for which sensors have collected data from satellites, and the second layer represents root zone storage. This version runs on a daily time step or shorter as well. Input data that this model uses are daily precipitation values (P), air temperature values (T), and potential evapotranspiration (PET) for selected catchments. The graphical structure of the TUW model is presented in Fig. 3.1, where all processes and parameters belonging to them are presented.

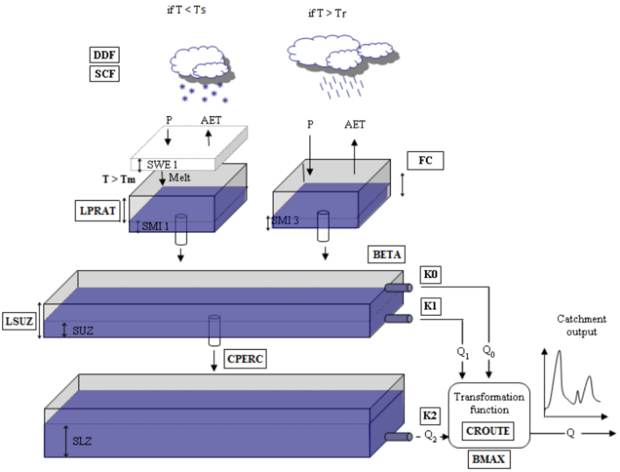

Fig. 3.1 Schematic representation of the TUW model (Kubáň 2021)

All the model's parameters are part of the R library (Viglione 2020), which is used for multi-objective calibration. Fig. 3 .2 presents the schematic structure of a dual soil moisture layer introduced in the HBV model and applied in the TUW model dual version.

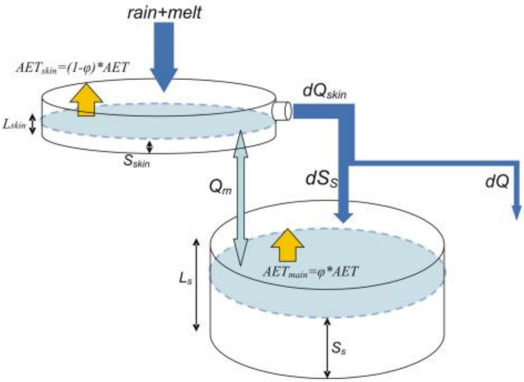

Fig. 3.2 Scheme of the dual soil moisture layer concept introduced in the HBV model and applied in the TUW model dual version (Parajka 2009)

One of the aims of this study is to run different calibration scenarios in the model where it was run:

- Discharge only (Q),
- Discharge and soil moisture (Q + SM)

Those scenarios are then divided into two different spatial divisions:

- Elevation zone catchment division (*ez*)
- Land cover zone catchment division (*lc*)

And two different temporal, seasonal divisions of data:

- Reference period (*ref*)

- Summer period (*summ*)

Based on data availability and to successfully evaluate the calibration and validation efficiency indicators, it was decided that the calibration period should be seven years from 01.01.2007 to 31.12.2014. In calibration, a warm-up period of 304 days was used. During calibration, two periods were evaluated. The period from 01.01.2007 to 31.12.2014 was first used without "masking" any day or season. This period is referred to as the "reference" period (later in the text, the label for this period is marked as "*ref*"). The other period subtracted from the referenced one is 01.01.2007 to 31.12.2014, but only the summer period was filtered out. More precisely, only June, July, August and September data from 2007 to 2014 were used for calibration evaluation. This period is referred as the “summer” period (in the text is marked as “*summ*”).

Model efficiency was calculated as a combination of NSE and logNSE coefficients:

$$ME_Q = \frac{(NSE+logNSE)}{2} \tag{3.1}$$

In the multi-objective calibration it was set different weights for Model efficiency s (OF) representing the weight both on runoff model efficiencies and soil moisture. Weights w_Q are ranging from 0 to 1 with step 0.1 ($w_Q = 0.05$ and $w_Q = 0.95$ are also used) :

$$\mathrm{OF} = w_Q * \left(1 - ME_Q\right) + \left(1 - w_Q\right) * (1 - ME_{SM}) \tag{3.2}$$

Where: w_Q represents the weight on runoff model efficiency.

ME_{SM} represents the model efficiency for soil moisture.

To evaluate the similarity between observed and simulated results, the best model parameters gained throughout each period of the calibration process were validated. More precisely, for the reference period in validation, the period used was from 01.01.2015 to 31.12.2019 without any masking. Equivalently, for the summer period, where only data for June, July, August and September was used for calibration evaluation, the subtraction was the same in the validation process. Subsequently, the model efficiencies and soil moisture correlation were calculated in the same manner as described previously.

The meticulous calibration process of the TUW model was followed by validation of the achieved results. More precisely, the regionalisation approach strategy was chosen. This approach involves the catchment "donor", representing Váh-Liptovský Mikuláš and the catchment "receiver", which is Jalovecký potok. In this case, the optimal parameters found in the reference and summer period for the elevation zone strategy and land cover strategy are transferred from the donor catchment and used in running the model validation for the catchment receiver.

4. Study area

For this study, Váh-Liptovský Mikuláš catchment was chosen which is part of the Váh catchment located in the north-east part of Slovakia. The gauging station Váh-Liptovský Mikuláš is the ending profile above the Liptovská Mara water reservoir with an area of catchment of 1107.21 km^2. Fig. 4.1 represents the location of the catchment in Slovakia, as well as the detailed elevation course of the area.

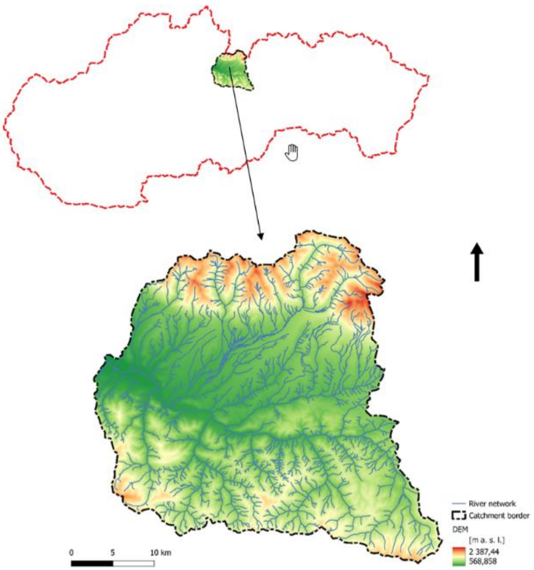

Fig. 4.1 Location of the Váh-Liptovský Mikulaš catchment and the representation of the river network on a digital elevation model with pixel size 20 meters

For the ungauged catchment and validation of the gained results, the Jalovecký potok catchment was selected (Fig. 4.2). This catchment is part of the Tatra National Park. The area selected for this study is estimated to be 22.15 km^2. According to the digital elevation model, the height of the catchment ranges from 818 to 2147 m above sea level.

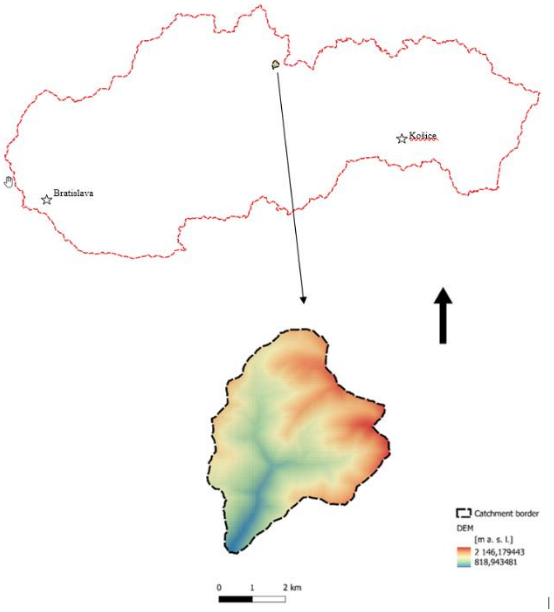

Fig. 4.2 Location of the Jalovecký potok catchment and the representation of digital elevation model with pixel size 20 meters

5. Results

5.1 Results for the calibration period from 2007-2014

Model efficiencies and the correlation values are presented separately in the figures below for a better graphical representation of the achieved results, as shown in Fig. 5.1. as the weight on the runoff increases, the model efficiency values steadily grow until 0.85 (where weight is $w = 0.6$) for the elevation zones variant in the reference period. In the summer of the same variant, the maximum values are noted in $w = 0.6$, $w = 0.7$ and $w = 1$, where all three values equal 0.84. When it comes to the land cover zones variant of catchment division, those values generally reach lower numbers. The maximum value of 0.82 was reached in the case of single objective calibration, where the maximum weight is assigned to runoff (*w* = *1*).

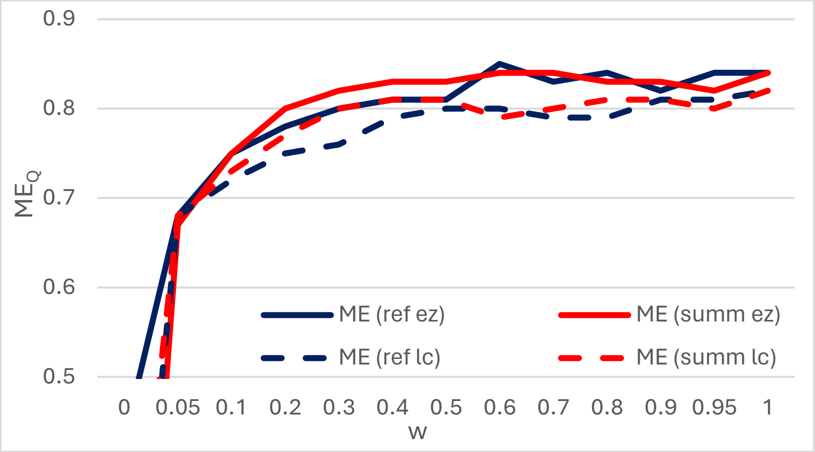

Fig. 5.1 Representation of the model efficiencies (ME_Q) results for the reference period (ref) for elevation zones (ez), and for the land cover zones (lc) where no month was masked, as well as the results for summer period (summ) where all months were masked besides June, July, August and September in the period of calibration (2007-2014).

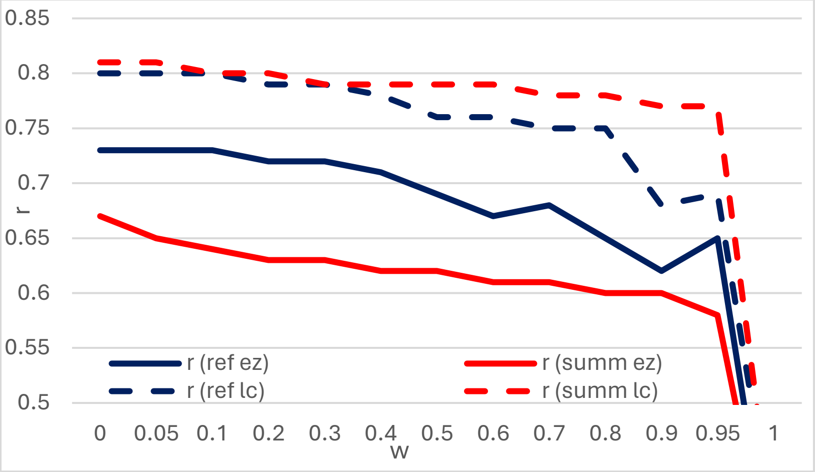

Fig. 5.2 Correlation values of soil moisture in the reference period (ref) where no months were masked, and in the summer period where all months were masked for soil moisture data besides June, July, August and September (summ). The graph represents elevation zones (ez) correlation values and land cover zones values (lc).

In the Fig. 5.2 the graphical representation of the correlation values results is shown. The lines below show a correlation between observed and modelled soil moisture values. The combination of blue and red lines shows correlation values, including all the months in a calibration period (2007-2014). It can be seen that the overall correlation values (*r*) are reaching higher values, ranging from 0.67 to 0.81 for weights ranging from 0 to 0.1 on runoff. If the values are observed in a more detailed way, the higher correlation values are gained in the land cover catchment division approach - r (*ref lc*) and r (*summ lc*).

5.2 Results for the validation period from 2015-2019

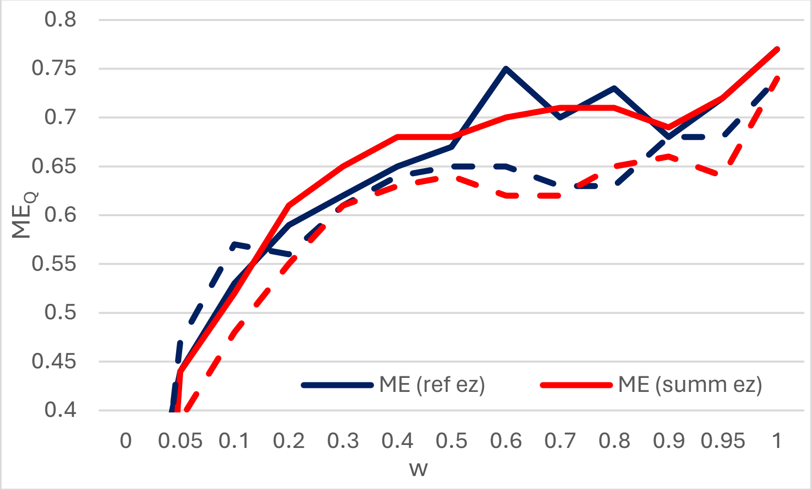

Fig. 5.3 Representation of the Model efficiency (ME_Q) results for the reference period (ref) for elevation zones (ez), and for the land cover zones (lc) where no month was masked, as well as the results for summer period (summ) where all months were masked for soil moisture evaluation besides June, July, August and September from 2015-2019.

Higher values have been achieved for elevation zone (*ez*) division in both reference period (*ref*) and summer period (*summ*) ME_Q (*ref ez*) = 0.77 and ME_Q (*summ ez*) = 0.78 for the highest weight on runoff. Regarding land cover division results, the highest values were achieved when the weight on runoff was the highest, ME_Q (ref lc) = 0.74 and ME_Q (*summ lc*) = 0.74.

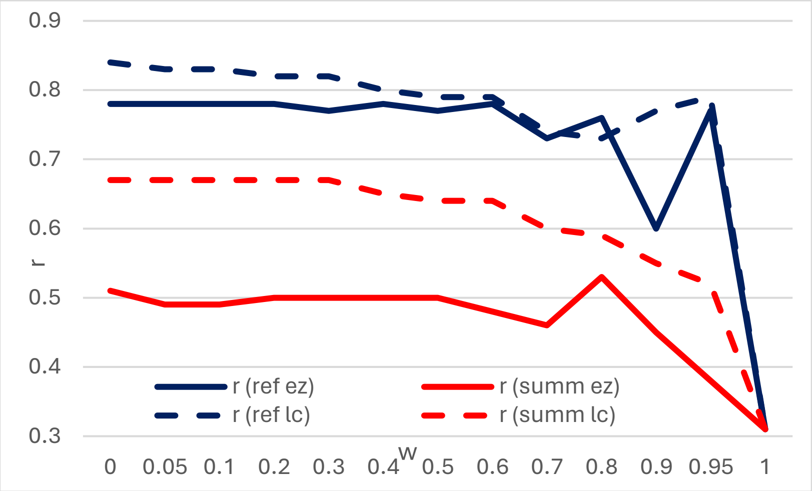

Fig. 5.4 Results of the mutual correlation of the soil moisture for all the elevation zones (ez) and for land cover zones (lc) for reference period (ref) where no month was masked and summer period (summ) of calibration where all months were masked for soil moisture evaluation besides June July, August and September from 2015-2019.

Fig. 5.4 shows that the values of land cover zones acquired higher values than those in land cover zones, and they made the biggest difference in weights from *w = 0.5* to *w = 0.8*.

6. Conclusion

Key findings offered from conducted research, in general, could be grouped according to the given aims of the study. Favourable results were achieved by opting out of multi-objective calibration as opposed to a single objective, considering all the calibration scenarios and seasonal components. Incorporating the land cover spatial division positively affected hydrological modelling in calibration and the validation period. The study identified the favourable performance of the model when soil moisture data was incorporated, more particularly when 60% of the weight was given to runoff and 40% to soil moisture model efficiency of runoff results (ME_Q) decreased by at least 4% (for the *summ lc* scenario in calibration period) opposed to the single-objective case. In this case, soil moisture correlation has increased to 108% as opposed to the case when the weight was only on runoff. This performance was steady even when 80% of the weight was given to runoff and only 20% to the soil moisture. ME_Q has also decreased by at least 4% in this calibration approach, but soil moisture correlation increased to 97%. During the calibration period, the model showed a steady decline in soil moisture correlation with increased weight on runoff; however, the model performed better with land cover division. When it comes to validation period when runoff was given 60% of the weight the *lc* scenarios declined to 12% (16% for summ lc), however soil moisture correlation improved to 106% (155% for summ lc).

The broader implications of this study can confirm previously stated vital findings, such as soil moisture as an additional component added to a conceptual model like TUW, which can significantly enhance the internal processes of the model and consequently improve runoff predictions in selected catchments. Reflecting on the thesis journey completion highlights the immense importance of having additional components available for hydrological modelling. This additional information broadens views about catchment behaviour and thus strengthens knowledge about prediction improvements of discharges and soil moisture.

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