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Evaluating the impact of satellite soil moisture data as an additional component in the calibration of a conceptual hydrological model

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Abstract: This study proposes a new method for dividing a catchment with the aim of testing it in the calibration process of a conceptual hydrological model. The new catchment division is reflected in having different land cover zones and the input data prepared in a semi-distributed way. This study also explores the impact of satellite soil moisture data when multi-objective calibration is used with the land cover zone divisions of a catchment while assigning different weights to runoff ranging from 0% to 100% (with a 0.05 step). The results indicate that using a weight range of 60% to 80% on a runoff provides optimal results, bettering both the runoff model's efficiency and soil moisture correlation. For further validation of the internal parameters and processes, the field capacity and evapotranspiration of the catchment were monitored. In regions with specially limited in-situ soil moisture data, satellite-derived data can contribute as an scarce additional component of the land cover division that can point out areas of the most reliable soil moisture information.

Keywords: Hydrological modelling; Soil moisture; ASCAT; Multi-objective calibration; Land cover zones.

INTRODUCTION

The calibration of hydrological models is an important step towards finding the best possible parameters of a hydrological model, that can replicate events in nature and, more specifically, in a catchment. For years, hydrological modelling was based on the calibration of parameters estimating one variable, and it was most often the runoff component that was estimated. As remote sensing products have become more accessible to the scientific community, the possibility and need to calibrate additional components provided by this technology have risen. Initial studies used coarse soil moisture (SM) products (e.g., ERS (Parajka et al., 2009)), while the potential for improving water balance modelling was limited to flat, arable land areas. Recent advances and the improved spatial and temporal resolution of new satellite missions (e.g., Sentinel missions) and new methods used for mapping satellite soil moisture (e.g., the DIREX directional resampling parameters) have improved soil moisture estimates, which have resulted in the improvement of water balance simulations (e.g., Kubáň et al., 2021; Tong et al., 2021). These studies have tested the ASCAT soil moisture dataset for the calibration of large number of catchments in Austria and found that in approximately 73% cases, using soil moisture as an additional component improved the model's calibration. Most of the improvements were recorded in catchments with a large proportion of arable lowland areas, as opposed to catchments with significant forest coverage. The model calibration in these cases, however, did not specifically account for spatial patterns of land cover. The role of the spatial variability of vegetation and different land covers on the efficiency of the assimilation of satellite soil moisture in calibrating hydrological model is therefore still not well understood.

The main research objective of this study is to evaluate the efficiency of a strategy that uses spatial units of land cover in the multiple objective calibration of a conceptual hydrological model. Previous studies have used satellite soil moisture in the calibration of lumped hydrological models or models distributed in elevation zones (Kubáň et al., 2021; Tong et al., 2021). The novelty and aim of this study is to split a research catchment into land cover zones, assess the runoff and soil moisture model efficiencies, and then compare them to the traditional approach (i.e., a model calibrated based to the elevation zones).

The study is structured as follows: The Methodology section describes the conceptual hydrological model and the proposed calibration and validation strategy. The Data section describes the catchment studied, the climate and hydrological data, and the satellite soil moisture product. The Results section presents the results and insights achieved while using soil moisture data to calibrate the hydrological model. Finally, the Discussion section compares the results with previous research, outlines the study's possible limitations, plans for future work, and developing new ideas and summarises the implications of the findings for future hydrological modelling.

METHODS AND MATERIAL

Hydrological model

The conceptual rainfall-runoff model used in this study is the dual-layer version of the Technische Universität Wien (TUW) model (Viglione and Parajka, 2020). This hydrological model replicates the structure of the Hydrologiska Byråns Vattenbalansavdelning model (HBV (Bergström, 1992)) and comprises three routines: snow, soil moisture, and flow routing. The dual version of the TUW model splits a soil layer into top and root zone storages. While the top soil layer matches the skin soil moisture observed from satellites, the root zone storage is represented by a satellite soil water index. The dual layer TUW model used in this study runs on a daily time step. The data input

are the daily precipitation values (P), air temperature values (T), and potential evapotranspiration (PET). The snow routine accumulates water from melting snow in the given catchment area through a straightforward degree-day concept (Parajka et al., 2007). This involves utilising a degree-day factor (DDF) and a melt temperature parameter (T_M). To address the deficit in precipitation measurements caused by snowfall, a snow correction factor (SCF) is applied. Additionally, a threshold temperature interval (T_R – T_S) is employed to differentiate between rainfall, snowfall, and a combination of rain and snow.

The input of rain and snowmelt to runoff (ΔS_{UZ}) is computed as a function of the top soil moisture layer (S_{SM}) and two parameters, i.e., the maximum soil moisture storage (FC) and non-linear parameter for runoff production (BETA):

$$\Delta S_{UZ} = (S_{SM}/FC)^{\beta}(P_R + M) \quad (1)$$

The actual evaporation (E_A) is determined through the calculation of potential evaporation (E_P) using the linear function from the top soil moisture layer:

$$E_A = E_P \frac{S_{SM}}{LPrat} \quad \text{if } S_{SM} < LPrat \quad (2)$$
$$E_A = E_P \quad \text{if } S_{SM} \geq LPrat$$

where: *LPrat* - the parameter determining the limit for potential evaporation.

The runoff routine serves to simulate the course of surface and subsurface runoff. The routing on the hillslope is presented by two soil reservoirs: the upper (S_{UZ}) and the lower reservoir (S_{LZ}). Excess rainfall enters the upper zone reservoir and exits through three pathways (Laaha et al., 2016), runoff from the reservoir with a storage coefficient for a fast response (k1), percolation into the lower zone with a constant percolation rate (cperc); and if the retention amount is exceeded, the water flows out through an additional drain through coefficient for a swift response (k0). The lower zone releases water according to a slow storage coefficient (k2). Subsequently, the outflow from both reservoirs undergoes routing through a triangular transfer function, which represents the runoff routing in the streams (Parajka et al., 2007):

$$B_q = bmax - croute * Q_g \ \ if\ (bmax - croute * Q_g) \geq 1 \quad (3)$$
$$otherwise \quad B_q = 1$$

where: B_q is the base of a triangular transfer function, *bmax* is the maximum base at low flows.

In addition to the 15 original parameters of the TUW model, three additional parameters represent the soil layer. All the parameters with their ranges also used in this study are presented in Table 1.

All the parameters described are part of the R library called "TUWmodel_dual" (Viglione and Parajka, 2020), used for multi-objective calibration. Fig. 1 presents the schematic structure of a dual soil moisture layer introduced in the HBV model and applied in the TUW model's dual version.

The model was tested in a semi-distributed mode where the input data and results for the catchment area were prepared and calculated in two versions: 1) the newly proposed version of dividing the catchment area and consequently its data into different land cover zones, and 2) the standard version of dividing the catchment area and consequently its data into different elevation zones.

Calibration and validation of hydrological model

The previously described methods, were used in the process of calibrating of the model for different land cover and elevation zones. The approaches were organised as follows: calibration only of the on discharge (Q) and calibration on a combination of the discharge and soil moisture (Q + SM). These approaches were further categorised into two spatial divisions, i.e., the elevation zone catchment division (ez) and the land cover zone catchment division (lc) as well as two temporal divisions, focusing on the reference period (ref) and the summer period (summ). This structure allows for a comprehensive analysis of the model's performance under varying spatial and temporal conditions.

Table. 1. TUW model parameters and the range used in the model's calibration.

Parameter label	Description	Unit	Range
SCF	snow correction factor	[–]	0.9–1.5
DDF	degree day factor	[mm/degC/timestep]	0.0–5.0
Tr	threshold temperature above which precipitation is rain	[degC]	1.0–3.0
Ts	threshold temperature below which precipitation is snow	[degC]	–3.0–1.0
Tm	threshold temperature above which melting starts	[degC]	–2.0–2.0
LPrat	parameter related to the limit for potential evaporation	[–]	0.0–1.0
FC	field capacity, i.e., max. soil moisture storage	[mm]	0–600 mm
BETA	the non-linear parameter for runoff production	[–]	[–]
k0	storage coefficient for a very fast response	[timestep]	0.0–2.0 days
k1	storage coefficient for fast response	[timestep]	2.0–30.0 days
k2	storage coefficient for slow response	[timestep]	30.0–250.0 days
lsuz	threshold storage state, i.e., the start of a very fast response if exceeded	[mm]	1.0–100.0
cperc	constant percolation rate	[mm/timestep]	0.0–8.0 mm/day
bmax	maximum base at low flows	[timestep]	0.0–30.0 days
croute	free scaling parameter	[timestep^2/mm]	0.0–50.0 days^2/mm
fc_skin	field capacity, i.e., max. soil moisture storage of the top soil skin layer	[mm]	0.1–10
f_eta	non-linearity coefficient of runoff generation	–	0.7–0.95
k_moist	parameter for the fraction of the actual evaporation	–	5–15

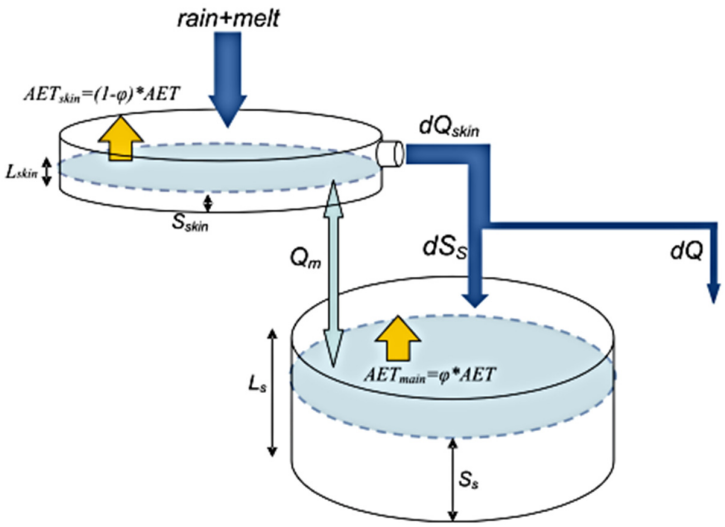

Fig. 1. Scheme of the dual soil moisture layer concept introduced in the HBV model and applied in the TUW model dual version (Parajka, 2009).

After defining the calibration scenarios, the next step is to gather all the required data describing the catchment to be further used throughout the calibration process. There is a need to define the absolute and relative areas of the catchment, and then to define the time series of the calibration process and the rest of the input data describing the catchment.

Based on the availability of data and in order 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. This period is the minimum duration necessary to attain a reasonably predictive performance of the model. The 7-year period chosen for this study had to meet all the criteria proposed in the studies mentioned above. A warm-up period of 304 days was used in the calibration. The calibration of the TUW model is run using the statistical software R (R Foundation for Statistical Computing).

In the calibration, the parameter optimisation was done using a method called Differential Evolution (Storn and Price, 2021). This genetic algorithm belongs among evolutional ones and uses principles such as heredity, mutation, natural selection, and crossover to find the right solution (Sleziak et al., 2021). In this study, the DEoptim library, which was used as an R library, implements the Differential Evolution algorithm, an evolutionary technique similar to classic genetic algorithms that help solve global optimisation problems (Ardia et al., 2011).

As indicators of agreement between the simulated runoff and the measured ones, two criteria coefficients were used: the Nash Sutcliffe coefficient (*NSE*) and the logarithmic Nash Sutcliffe coefficient (logNSE) (Nash and Sutcliffe, 1970).

$$NSE = 1 - \frac{\Sigma_{i=1}^{n}(Qobs - Qsimi)^2}{\Sigma_{i=1}^{n}(Qobsi - Qobs)^2} \quad (4)$$

$$logNSE = 1 - \frac{\Sigma_{i=1}^{n}(logQobsi - logQsimi)^2}{\Sigma_{i=1}^{n}(logQobsi - logQobs)^2} \quad (5)$$

where i represents the day of the simulated runoff observed, n represents the days for which the coefficients are calculated; Q_{obs} represents the observed runoff, and Q_{sim} represents the simulated runoff.

The model efficiency (ME_Q) was calculated as a combination of the *NSE* and *logNSE* coefficients:

$$ME_Q = \frac{(NSE + logNSE)}{2} \quad (6)$$

Different weights were assigned to the objective function (*OF*) in the multi-objective calibration, thereby balancing the emphasis between the runoff model efficiency and soil moisture. The weights for the discharge (w_Q) ranged from 0 to 1, with increments of 0.1 (including $w_Q = 0.05$ and $w_Q = 0.95$).

$$OF = w_Q * (1 - ME_Q) + (1 - w_Q) * (1 - ME_{SM}) \quad (7)$$

where w_Q represents the weight of the runoff model efficiency, and ME_{SM} represents the model efficiency for the soil moisture.

In order to be able to compare the simulated value of the root zone soil moisture by the model and the measured value of the root zone soil moisture, it is necessary to convert the simulated value with the use of the field capacity parameter (*FC*) through the equation:

$$SM_{sim} = SM_{simwp} * 100/FC \quad (8)$$

where SM_{simwp} represents the simulated values of the root zone soil moisture with the removed days of a warming period, and *FC* is the field capacity parameter with a range from 0–600 mm.

The indicator of agreement between the observed soil moisture and simulated values that were monitored was their mutual correlation (in this study marked as "*r*") for the whole time series. The general equation for calculating the correlation is presented in Eq. (8):

$$r = \frac{n\sum SM_{obs}SM_{sim} - (\sum SM_{obs})(\sum SM_{sim})}{\sqrt{[n\sum {SM_{obs}}^2 - (\sum SM_{obs})^2][n\sum {SM_{sim}}^2 - (\sum SM_{sim})^2]}} \quad (9)$$

where n represents the number of days entered into the correlation calculation; SM_{obs} represents an observed value of the soil moisture, and SM_{sim} represents the simulated value of the soil moisture.

Data – Study area

The research was conducted on a mountainous catchment located in the Western Tatra mountains the Váh-Liptovský Mikuláš catchment in Slovakia. The Váh-Liptovský Mikuláš gauging station is the ending profile above the Liptovská Mara water reservoir with a catchment area of 1107.21 km^2. The average altitude for the catchment is 1090.1 meters above sea level and a median of 1006.0 meters above sea level. Fig. 2 represents the location of the catchment in Slovakia, as well as the detailed elevation course of the area.

This study also focuses on monitoring the runoff and soil moisture estimations of different spatial zones; the catchment is therefore divided into different elevation zones and land covers. As the height of the Váh-Liptovský Mikuláš catchment ranges from 400 m a.s.l to 2400 m a.s.l., 200 meters ten elevation zones were established for each zone. This division into 200 meters per elevation zone was an experiment in previously cited studies (Kuban et al., 2022; Tong et al., 2021) and set the starting point for this research. According to this division, the Váh-Liptovský Mikuláš catchment's lowland zones are primarily concentrated in the central part of the catchment, whereas the highland zones are located in the northern and southern parts of the catchment. From a morphological-morphometric point of view, all the types of covers occur in the territory of the Váh sub-catchment. The Váh sub-catchment passes through high and mid-mountainous areas. Considering its relatively large area, the geological conditions of the basin can be characterised as relatively homogeneous. When it comes to the vegetation structure and land cover, which are based on the CORINE Land Cover nomenclature (CLC) (Copernicus Land Monitoring Service), throughout the catchment can be found various dominant types of forests (broad-leaved, coniferous and mixed-type forests), then semi-natural areas, followed by agricultural land cover and artificial surfaces. For the land cover zones of Váh-Liptovský Mikuláš, four classes of land covers were defined based on the CLC nomenclature. To better distinguish the land covers and focus more on studying the calibration results for the forests and agriculture areas, the original CLC nomenclature was slightly modified for this study in a way where wetlands and water bodies were merged into semi-natural areas as one class.

Regarding the percentual analysis representation of each elevation zone containing each land cover zone, the agricultural and forest areas are the majority in the lower elevation zones (from 400 to 1400 m a.s.l.). Semi-natural areas dominate the upper elevation zones (from 1400 to 2400 m a.s.l.). Regarding the percentual analysis representation of the land cover zone containing each elevation zone, agricultural areas dominate in elevation zone 2 (from 600–800 m a.s.l.), and forest areas dominate in elevation zone 3 (from 800–1000 m a.s.l.).

During the calibration, two time periods were evaluated. The period from 01.01.2007 to 31.12.2014 was first used without "masking" any day or season (i.e., masking winter months or the days with snow cover identified, etc.). 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 the calibration evaluation. This period is referred to as the "summer" period (in the text is marked as "*summ*"). In Table 2 variants of spatial zones, and periods and data which were used for these variants in calibration and validation periods are stated.

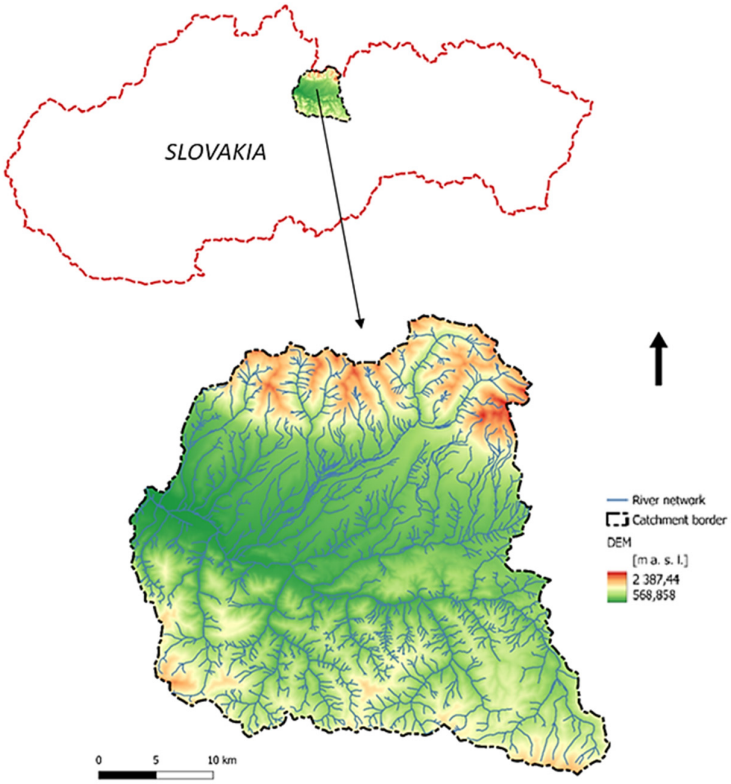

Fig. 2. Location of the Váh-Liptovský Mikuláš catchment within Slovakia (top) and the representation of the river network on a digital elevation model with a pixel size of 20 meters (bottom).

Table. 2. Breakdown of the calibration and validation variants.

Variant no.	Abbreviation	Calibration period	Validation period	Note
Variant 1	*ref ez*	01.01.2007 – 31.12.2014	01.01.2015–31.12.2019	Input data for n the catchment are divided into elevation zones, and the whole period was used.
Variant 2	*summ ez*	01.01.2007 – 31.12.2014	01.01.2015–31.12.2019	Input data for the catchment are divided into elevation zones, and only data for June, July, August and September was used.
Variant 3	*ref lc*	01.01.2007 – 31.12.2014	01.01.2015–31.12.2019	Input data for the catchment are divided into land cover zones, and the whole period was used.
Variant 4	*summ lc*	01.01.2007 – 31.12.2014	01.01.2015–31.12.2019	Input data for the catchment are divided into land cover zones, and only data for June, July, August and September was used.

Hydrological data

To successfully run the model, importing the numerical, interpolated data about the precipitation (P) measured across the catchment on rainfall stations in both the catchment's immediate and more comprehensive surroundings was necessary. The precipitation values were acquired by using the Universal Kriging precipitation interpolation method (Zimmerman et al., 1999). The total number of stations used for the precipitation interpolation was 28; the Slovak Hydrometeorological Institute, the Institute of Hydrology, and the Slovak Academy of Sciences provided the data. The temperature values were also gained by interpolating the data collected at the climatological stations in the catchment's immediate and more comprehensive surroundings. The total number of stations for interpolation was 7, and the method applied was the Elevation Gradient method. Finally, the data calculated about potential evapotranspiration (PET) using the Blaney-Criddle empirical equation (Parajka et al., 2003) on the catchment were also used. The measured runoff (Q) in the catchment's end profile and the soil moisture for the root zone (SM) data were imported for the data simulation process. Because of the need for data from rainfall or climatological stations for every point in the catchment or its near surroundings, the data from the climatological or rainfall stations needed to be spatially interpolated to provide more spatially denser data for the modelling. To ensure that an artificially calculated temperature inversion did not occur in interpolation process, it was agreed that for the highest altitude values in the catchment, the temperature would be taken from the measurements of the nearest climate station.

Satellite soil moisture data

The soil moisture data representing the root zone were acquired as a product of cooperation between the Department of Geodesy and Geoinformatics at the Technical University of Vienna (TUW), the Institute for Hydraulic Engineering and Engineering Hydrology (TUW), and the Department for Land and Water Resources Management at the Slovak University of Technology (STU) in Bratislava. The data version that was acquired for this study is dated as of November, 2022. Soil moisture data is constantly updated and improved by its providers, as is the length of the time series that is offered for testing.

The METOP-A, -B, and -C (Meteorological Operational) flying satellites operated by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) were responsible for carrying Advanced Scatterometer sensors (ASCAT) on its board. These sensors are then used to retrieve soil moisture data. Large-scale soil moisture patterns can be captured with such a wide swath. It is operated in the C- band, meaning that it has a frequency of around 5.3 GHz. An ASCAT scatterometer is a suitable sensor for the retrieval of soil moisture as it is in the range of microwave frequencies (< 10 GHz), where the addition of liquid water to soil strongly increases the soil's dielectric constant. (Wagner, 2013). There is the gloomed signal response of the backscattering coefficient in the presence of vegetation. Therefore, retrieving soil moisture data could be challenging in areas with dense vegetation. When it comes to the challenges of data retrieval, there is a need to mention the roughness of the surface, mountainous areas, and areas with a high frequency of radio signals (EODC, 2021). Based on its user manual (EODC, 2021), the ASCAT DIREX Soil Water Index (*SWI*) 0.5 km product provides estimates of the Soil Water Index. The soil water content profile is placed on a 500 m spatial sampling grid, which was also used in this study. The *SWI* represents the soil moisture content to the first 1 m of the soil depth in relative units (%). An essential parameter for modelling water infiltration into deeper layers is the characteristic length of time, called the T-value (the more significant the *T*-value, the smoother the *SWI* is (EODC, 2021)). The following Eq. (10) (EODC, 2021) describes how the soil moisture values observed are transformed into *SWI* values.

$$SWI(t_n) = \frac{\Sigma_i^n SSM(t_i) e^{-\frac{t_n - t_i}{T}}}{\Sigma_i^n e^{-\frac{t_n - t_i}{T}}} \quad (10)$$

where: t_n represents the observation time of the current measurements, t_i represents the observation times of the previous measurements, *SSM* represents the Surface Soil Moisture.

The *T*-value determines how fast the weights become smaller and how strongly *SSM* observations taken in the past influence the current *SWI*. This study only used $T = 40$, which represents the root soil layer.

RESULTS

Results for the calibration period from 2007–2014

Every calibration scenario was run for different weights on the discharge values in the range $w = 0$ to $w = 1$ with a step of 0.1. The weights $w = 0.05$ and $w = 0.95$ were also used for better monitoring leaps between a lower weight of the runoff and the next-to-maximum weight of the runoff. As shown in Fig. 3, as the weight on the runoff increases, the model efficiency values (ME_Q) steadily grow until 0.85 (where the weight of the runoff is $w = 0.6$) for the elevation zone variant in the reference period. In the summer period of the same variant, the maximum values

are noted as $w = 0.6$, $w = 0.7$ and $w = 1$, where all three values equal 0.84. When it comes to the land cover zone variants of the catchment divisions, those values generally achieve lower numbers. The maximum value of 0.82 was reached in the case of the single objective calibrations, where the maximum weight is assigned to the runoff ($w = 1$).

Fig. 4 shows a graphic representation of the correlation value results. The lines below show the correlation (r) between the observed and modelled soil moisture values. The combination of blue and red lines shows the correlation values, including all the months in the 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 of the runoff. If the values are observed in more detail, the higher correlation values can be seen to be gained in the land cover catchment division approach – r (*ref lc*) and r (*summ lc*).

When monitoring the internal parameters of the model was performed, the parameter evaluated was the Field Capacity (FC) parameter, which represented the maximum soil moisture storage. FC is expressed in [mm], where the values range from 0–600 mm. Figure 5 shows that the elevation zone division resulted in lower values than the *lc* approach from $w = 0.1$ to $w = 0.7$. The values for *ez* range from 37.93 to 237.05 mm, and the *lc* approach ranges, from 47.43 to the highest value of 563.27 mm.

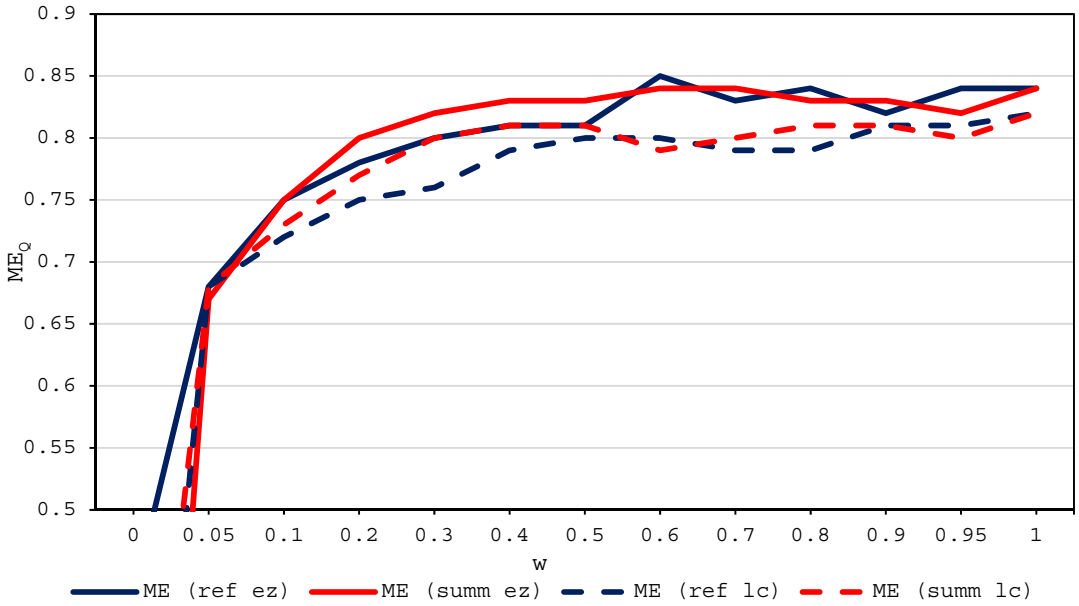

Fig. 3. Representation of the model efficiency (ME_Q) results for the reference period (ref) for the elevation zones (ez) and the land cover zones (lc) where no month was masked, as well as the results for the summer period (summ) where all the months were masked except for June, July, August and September in the calibration period (2007–2014).

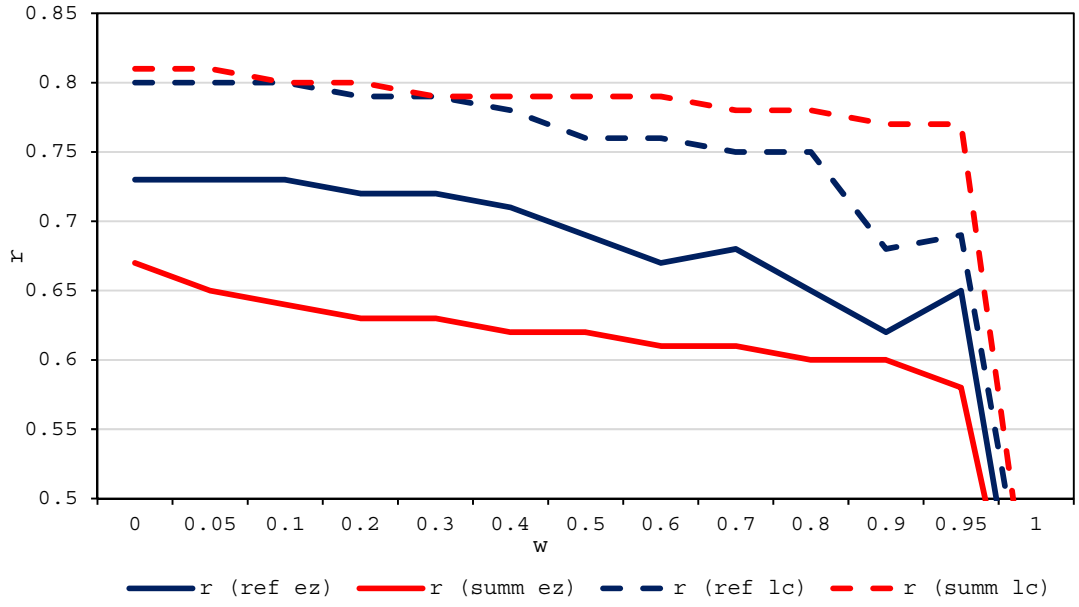

Fig. 4. Correlation values of the soil moisture in the reference period (ref) when no months were masked, and in the summer period when all the months were masked for the soil moisture data except for June, July, August and September (summ). The graph represents the elevation zones (ez) correlation values and land cover zone values (lc).

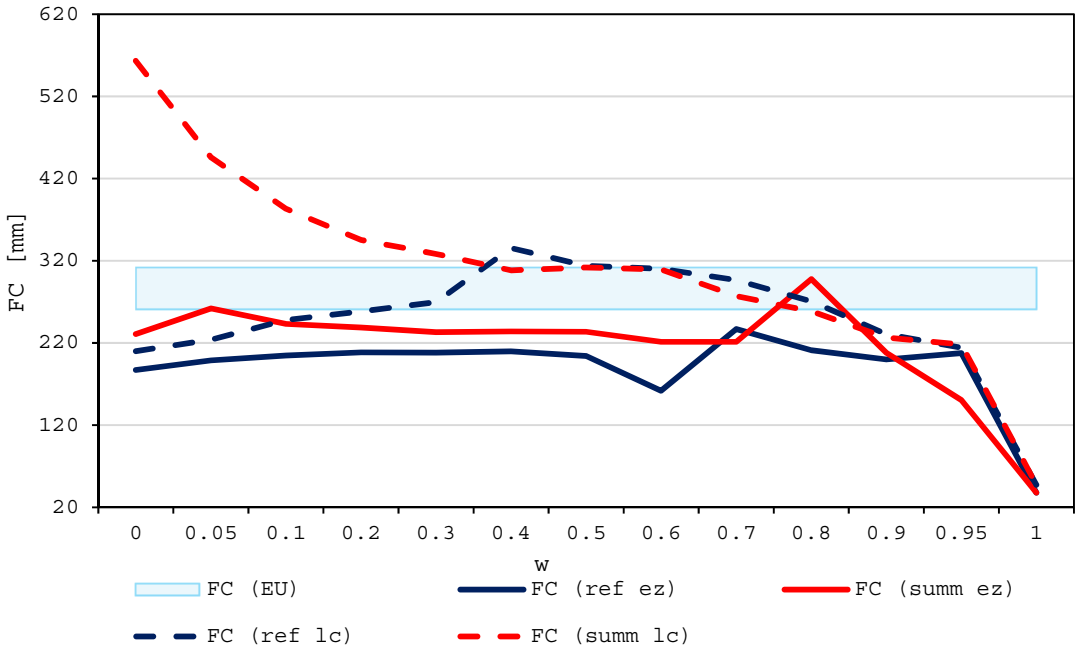

Fig. 5. Values of the field capacity (FC) expressed in [mm] parameters for different weights on runoff for the reference period (ref) where no months were masked and also in the summer period, when all the months for the soil moisture evaluation were masked except for June, July, August and September (summ) for the elevation zones (ez) and land cover zones (lc) from 2007–2014. The pale blue area represents the range of the minimum and maximum FC values for the Váh-Liptovský Mikuláš catchment (FC (EU)) estimated by the 3D Soil Hydraulic Database of Europe at a 250 m resolution (Tóth et al., 2017).

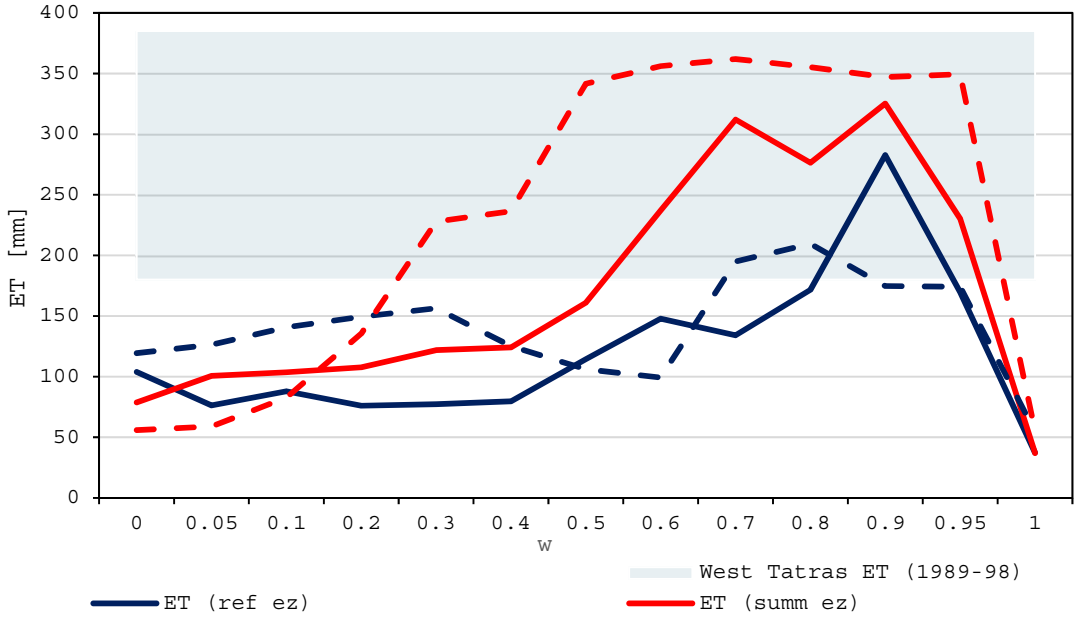

Fig. 6. Values for the modelled evapotranspiration (ET) represented for the calibration period from 2007–2014 for the four calibration scenarios (ref ez, summ, ez, ref lc, summ lc) together with the range of average values calculated in the West Tatras (West Tatras ET (1989–1998)) in the period from 1989–1998.

Most FC numbers fall within 150 to 300 mm, with the sharpest value falling in the single objective calibration approach. The mean value estimated from the 3D Soil Hydraulic Database of Europe at a 250 m spatial resolution (Tóth et al., 2017) for the whole Váh-Liptovský Mikuláš catchment is equal to 284 mm, which is within the interval of the majority of the FC values calculated by the TUW model for this study. the pale blue zone on the graph shows the minimum (211 mm) and maximum (310.5 mm) field capacity values calculated for the Váh-Liptovský Mikuláš catchment based on the estimations in the 3D Soil Hydraulic Database of Europe.

When it comes to monitoring the internal processes of the model, the modelled evapotranspiration was calculated to present seasonal and spatial changes in the catchment. The results for the four calibration scenarios are presented in Fig. 6, which is also presented as the range of values calculated for four

valleys (Žiarska, Račkova, Tichá, Kôprova valley (Holko et al., 2001) located in the West Tatras near the Váh-Liptovský Mikuláš catchment. These values range from 180 mm to 385 mm, and are presented as the pale blue area on the graph. The highest values are expected for the elevation and land cover zone divisions in the evaluation of the summer season. For the elevation zone division, the values for the evapotranspiration are within the pale blue area, representing the average ET values for West Tatras valleys, from $w = 0.5$ to $w = 0.9$ and range from 161 mm to 230 mm.

Meanwhile, those weights range from $w = 0.3$ to $w = 0.95$ for the land cover divisions in the summer season, and the values for the ET range from 228 mm to 349 mm. As for the reference period, there are more months included in the evaluation; it can be seen that the window span of ET values for Váh-Liptovský Mikuláš within the ET values for the West Tatras valleys is much shorter compared to the summer season. These values are presented for elevation zones when $w = 0.8$ to $w = 0.95$; land cover zones are presented from $w = 0.7$ to $w = 0.9$.

Results for the validation period from 2015-2019

The period for which the results are presented is from 2015 to 2019. Fig. 7 presents the results for the runoff model efficiency where it can be seen that higher values have been achieved for the elevation zone (*ez*) division in both the reference period (*ref*) and summer period (*summ*) ME_Q (*ref ez*) = 0.75 and ME_Q (*summ ez*) = 0.77 for the highest weight of runoff. Regarding the land cover division results, the highest values were achieved when the weight of runoff was the highest, i.e., ME_Q (ref lc) = 0.74 and ME_Q (*summ lc*) = 0.74. The most significant difference between the periods and zones can be seen in the range of weights from $w = 0.5$ to $w = 0.8$.

While the model efficiency values are increasing towards the highest weight of the runoff, the correlation values are dropping towards the highest weight of the runoff ($w = 1$), (Fig. 8). The values of the soil moisture correlation, which belong to the land cover division, achieved a higher correlation than those in the elevation zone divisions. Only one value of the elevation zones in the reference period with higher correlation results is in $w = 0.8$ where r = 0.76, and the second highest weight value on the runoff of $w = 0.95$, where r = 0.76; then the values drop to 0.31. On the other hand, for the land cover division correlation results, the highest results achieved are in the reference period (*ref lc*), with the maximum r = 0.84, when the weight is only on the soil moisture ($w = 0$).

The task of calibrating and validating the conceptual TUW rainfall-runoff model was surrounded by different scenarios and catchment spatial divisions. These processes serve as a stable path in ensuring the reliability and accuracy of the predictive possibilities of the model for further studies and practical use. This work also aims to identify the highest efficiency achievable in the runoff simulation and soil moisture correlation and to identify the optimal weight values on the runoff that achieve those objectives. The model was run as, where the model inputs were used for two different divisions of the catchment studied, i.e., elevation and land cover zones. The semi-distributed method of running the model where the catchment was divided into 200 m zones, which was the same as in this study, was part of many previous studies recently (Kubáň et al., 2021; Kuban et al., 2022; Tong et al., 2021). However, the objectives of those studies were focused on multiple catchments located in Austria (more than 200) at different elevations (e.g., from 38 m a.s.l. up to 3798 m a.s.l.) and with various slopes and land cover. On the other hand, as this study focuses only on one catchment and a more in-depth approach, there are certain limitations as to the possibility comparisons of results. Additionally, as a novelty, this study offers a semi-distributed way of running the TUW dual version model using different land cover zones in the catchment, which brings a new approach to interpreting the previously achieved results.

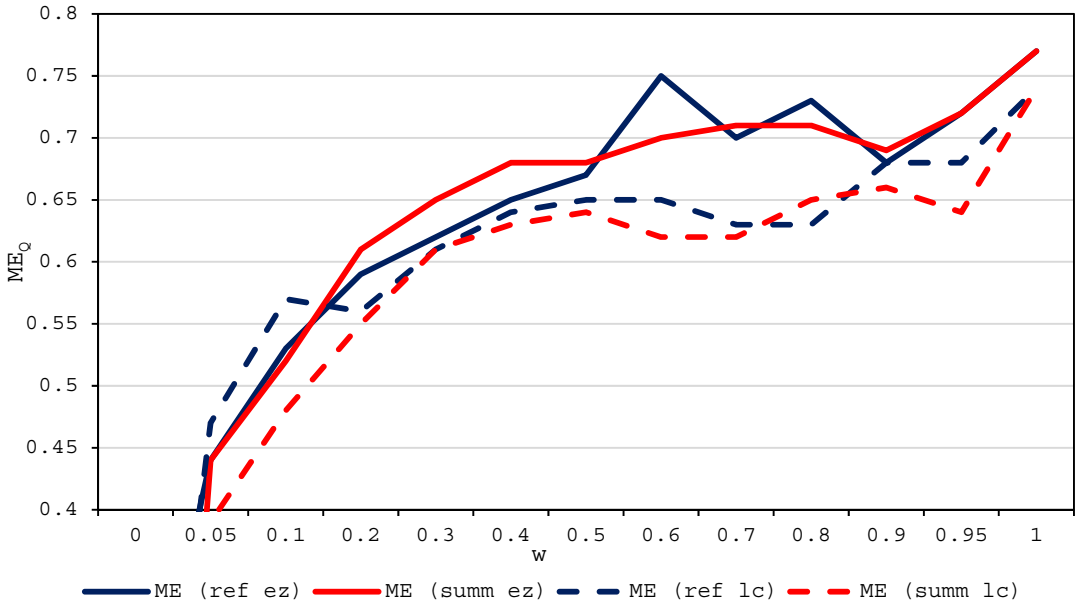

Fig. 7. Representation of the model efficiency (ME_Q) results for the reference period (ref) for the elevation zones (ez) and the land cover zones (lc) where no month was masked, as well as the results for the summer period (summ) where all the months were masked except for June, July, August and September in the validation period (2015–2019).

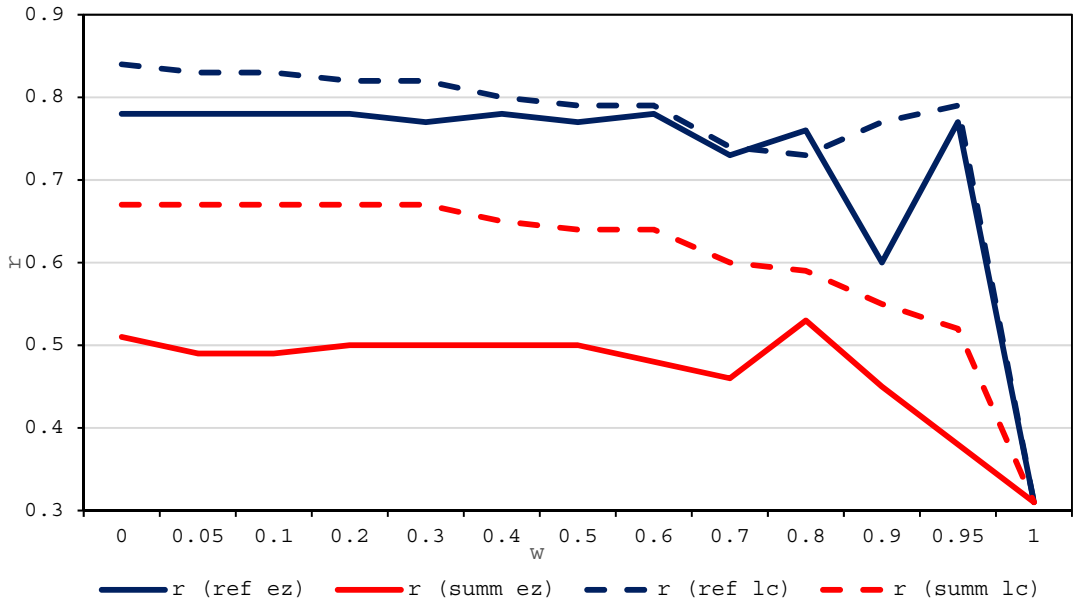

Fig. 8. Results of the mutual correlation of the soil moisture for all the elevation zones (ez) and for the land cover zones (lc) for the reference period (ref) where no month was masked and the summer period (summ) of the calibration where all the months were masked for the soil moisture evaluation except for June July, August and September from 2015–2019.

Various studies have researched the topic of improving the performance of a hydrological model with the implementation of remote-sensed data (e.g., soil moisture) and, in this way, testing the multi-objective calibration approach. Some of them conclude that single-objective calibrations can lead to increased errors in some characteristics of other properties (Mostafaie et al., 2018), and some of them conclude that using remote-sensed data of soil moisture leads to its better correlation in catchments, which in this study was also seen. An evaluation of the overall modelling research when soil moisture is used as an additional component of hydrological modelling in this study shows that the recommended optimal range of weights for further modelling research is between $w = 0.6$ and $w = 0.8$. In those weight ranges on runoff, both the runoff efficiency and soil moisture correlation are considered for different calibration scenarios. This range ensures high model efficiency while maintaining a balanced correlation with the soil moisture, making it suitable for hydrological modelling across different catchments with similar geomorphological and climatic characteristics.

Another favourable indication for using multi-objective calibration instead of single-objective calibration is reflected in the compared Field Capacity parameter (FC). More precisely, in this study, the focus was also set on comparing the FC parameter obtained due to the calibration process of the TUW model dual version and the FC parameter from the 3D Soil Hydraulic Database of Europe at 1 km and 250 m resolutions (Tóth et al., 2017). This European database utilises pedotransfer functions to analyse soil data. SoilGrids, global gridded soil information, offers highly detailed information on European soil properties, covering seven soil depths at 250 meter resolutions. Based on the calculations made in this consistent spatial soil hydraulic database, the average value gained for the Váh-Liptovský Mikuláš catchment is estimated at 284 mm. This value is calculated for the whole catchment. According to the database that was compared, the higher number is located in the central part of the catchment, where most of the agricultural areas are. In the northern and southern parts of the catchment, where the forest and semi-natural areas are mostly covered, the FC parameter had the minimum values according to the European database. Assume the EU soil database values were compared to those in a single objective calibration (the FC values with w = 1). In that case, these values would demonstrate that the single objective calibration values are significantly lower than the EU average estimation of FC for Váh-Liptovský Mikuláš. These results indicate the fundamental importance of the additional involvement of data in hydrological modelling (a multi-objective calibration), as opposed to a single objective calibration, which can lead to oversimplification of the results and may ignore aspects in the modelling that occur in between.

Moreover, the improved FC results, especially in the land cover division, confirm that incorporating land cover information in the hydrological model is crucial for monitoring change in this parameter across different land cover types. The modelled evapotranspiration values were compared to a study done in the West Tatras by Holko et al. (2001). The period for which this study was conducted was from 1989–1998. Regarding this study's results, it was found that using weights of $w = 0$ and $w = 1$ for the runoff (representing calibration only of the runoff or soil moisture) gave significantly lower ET values in every scenario. These lower values did not match the results from the West Tatras study. The most satisfactory ET results were achieved when 60% to 95% of the weight was given to the runoff, making this range suitable for further use and evaluation.

Regarding the possible limitations of this study, there are still unevenly distributed in-situ soil moisture monitoring stations, which would offer denser soil moisture data in the catchments. Their existence could be of immense importance when validating data offered from remotely sensed sources. In addition, satellite data can be skewed by the spatial variability of the catchment when it comes to capturing local events, such as rainfalls. There is more room for future work and development of this topic, mainly in calibrating the parameters in lowlands, and more agriculturally-focused catchments, and using both the skin soil layer and root zone soil layer from remotely sensed sources.

CONCLUSION

This study aimed to explore how additional data in the form of soil moisture improves the overall calibration of the hydrological TUW rainfall-runoff model in a dual version. Integrating satellite-derived soil moisture data focused on balancing the runoff efficiency and soil moisture correlation to improve hydrological predictions. 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's spatial division positively affected the hydrological modelling in the calibration and the validation periods. The study identified the favourable performance of the model when soil moisture data was incorporated, particularly when 60% of the weight was given to runoff and 40% to soil moisture. Regarding validation of the internal processes, the comparison of the FC values, from the calibration process, as a part of the validation of the internal processes of the TUW model with the 3D Soil Hydraulic Database of Europe (Tóth et al., 2017) indicated the minimal relative change in the land cover division scenario. The broader implications of this study can confirm vital previously stated findings, such as soil moisture as an additional component added to a conceptual model like the TUW, which can significantly enhance the internal processes of the model and consequently improve runoff predictions in selected catchments.

This study's results can appoint to variety of benefits and actual improvements of water regime. more particularly, the use of satellite-derived soil moisture data for improvement of runoff modelling and soil moisture correlation especially in those regions where in-situ data are limited or absent. The use of such data is helpful in filling the gaps in data availability enabling running hydrological models in different regions. Additionally, using different weights of runoff in modelling enables in-depth analysis of internal processes of the model as well as achieving optimal weight for both runoff and soil moisture and therefore enhancing model's ability to calibrate two components. By dividing the catchment into land cover zones in addition to elevation zones, the model becomes sensitive to the spatial variability of landscape which is beneficial in making hydrological predictions for those catchments with mixed land use areas.

While this study focuses on a specific mountainous catchment, Váh-Liptovský Mikuláš, the extension of the study research could be focused on more lowland catchment with the majority of agricultural land cover. In this way, the behaviour of the hydrological model could be tested in the conditions beneficial for satellite-derived soil moisture data and further could be researched on how the topographical component affect efficiency of the satellite data integration.

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