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Development and validation of an Approximate Redistributive Balance model to estimate the distribution of water resources using the WEAP: The lower Hron river basin, Slovakia

Miroslav KANDERA*, Roman VÝLETA

The Approximate Redistributive Balance (ARB) model integrated within the Water Evaluation And Planning (WEAP) software environment aims to retrospectively simulate the flows measured by water gauging stations with sufficient accuracy according to objectives of study. It does so by initially approximating the runoff distribution with a rainfall-runoff model along the modeled streams and then redistributing the difference between the sum of the total simulated runoff to the water gauging station and the flow in the water gauging station (cleaned of any anthropogenic influences). Due to its different approach to the modeling method and the user-friendly environment of the WEAP software, this model, with a relatively small scale of input data, retrospectively simulates flows along the modeled streams with a high degree of accuracy (NSE = 0.89 for similar hydrological regime of validation and calibration basins). This paper describes its development and basic characteristics and provides partial insights into the degree of accuracy with which it can simulate monthly streamflow at water gauging stations and along modeled rivers. It can therefore be a precise foundation for analyses of water management balance scenarios.

KEY WORDS: water balance, hydrological components, water evaluation and planning, water resources, model development

Introduction

To be able to create and analyze scenarios showing the impact of the water management on surface flows in the form of a balance, it is first necessary to specify what flow data representing the available source of water will be entered the balance equation. If it would be necessary to evaluate the flow regime along streams used for water management, rainfall-runoff modeling appears to be the only possibility. Within the modeling, the individual components of the hydrological cycle, such as runoff, infiltration, evapotranspiration, etc., whose interrelationships are not constant over time and in space, are defined. Therefore, almost all hydrological modeling is a cycle of the calibration, validation, and optimization of the model to refine these relationships and model the results to the required level (Sleziak et al., 2021). To use modeling in a quantitative water management balance, the evaluation of which is ongoing retrospectively in Slovakia by the Slovak Hydrometeorological Institute (2021), we started to develop a different approach based on redistributing runoff.

In previous papers (Kandera and Výleta, 2020; Kandera et al., 2021), we proposed an approach framework where, from a spatial point of view, the basin modeled was divided into two levels. The first level consisted of sub-basins, i.e., drainage areas bounded by stable water gauging stations with long and uninterrupted rows of observed flows. Each sub-basin thus had one outlet (closing) profile and could have several inlet profiles, from which runoff from higher sub-basins flowed into the given sub-basin. From a hydrological point of view, a sub-basin without any inlet profiles is, so to speak, the roof of the entire modeled basin. Both streams with water gauging stations and tributaries without them were modeled within the model. Since the WEAP software is a nodal model (Sieber and Purkey, 2015), a second basin subdivision level, namely, the level of the micro-basins, was used to partially simulate longitudinal runoff along streams. The modeled streams were divided into individual sections at regular lengths, and each section had its own drainage area, which was its micro-basin. Runoff from the individual micro-basins was calculated by distribution from the sub-basin under which the individual micro-basins fell. This procedure was based on the following equation:

$$Q_{c,i} = Q_{r,i} - X_i \qquad (1)$$

where

$Q_{c,i}$ – the cleansed outflow from a sub-basin in time step i [m^3 s^{-1}];

$Q_{r,i}$ – the calculated outflow from the sub-basin in time step i [m^3 s^{-1}];
X_i – the anthropogenic impact in time step i [m^3 s^{-1}].

The equation to calculate the outflow from the sub-basin is given in the form:

$$Q_{r,i} = Q_{out,i} - \sum Q_{in,i} \quad (2)$$

where
$Q_{out,i}$ – the streamflow measured in the water gauging station outlet of a sub-basin in time step i [m^3 s^{-1}];
$\sum Q_{in,i}$ – a summary of the streamflow measured in the inlet water gauging stations of the sub-basin in time step i [m^3 s^{-1}].

The cleansed outflow was subsequently distributed as runoff to selected reaches on the river network modeled based on the defined share of the individual micro-basins of the corresponding reaches. While this procedure made it possible to simulate the flow simply and accurately in the water gauging station, the distribution of the runoff along the modeled tributaries was relatively imprecise, as it was only based on the share of the micro-basins in the area, the total rainfall, and the difference from the average slope of the sub-basin. In the modeled basin, the unevenness of the variables affecting the basin's outflow regime over time and in space is fully manifested.
The main objective of this paper is to describe and evaluate the newly created ARB model and to underline its specific characteristics along with possible issues and how to handle them. The methodology developed was tested on the lower Hron river basin in Slovakia.

Methods and material

In this paper, we have developed a new methodology where the one-step distribution model is extended to a multi-step Approximate Redistributive Balance (ARB) model. In the WEAP software, it is possible to apply changes in the data structure of the model and thereby create a deeper structure of the model using the branching form of scenarios. From this point of view, it is possible to break down the structure of the model into the individual scenarios according to Fig 1.
The structure of the ARB model consists of several sub-models (i.e., a snow sub-model, runoff approximation sub-model, and redistribution sub-model). The task of this article is not to specify all the sub-models in detail but to outline a methodical procedure for solving the problem of the redistribution of the runoff from the basin. For this reason, we will mainly focus on a description of the approximation and redistributive sub-models.

Snow sub-model

The setup scenario represents an input scenario in which the individual variables, references to input data, and mutual relations of the individual variables are defined. The snow sub-model calibration scenario is a separate scenario from which only the calibrated parameters are subsequently taken. The snow sub-model was created out of the need for a compatible tool that, when using data from the precipitation, air temperature, and altitude, will provide sufficiently accurate data for the necessary approximation. In general, the snow sub-model can be described as a non-linear, deterministic, dynamic snow sub-model with (5) distributed parameters calibrated to the data of the snow water equivalent. The output of the sub-model is the calculated value of the snow water equivalent, which is then entered into the equation:

$$SWB_i = SWE_{i-1} - SWE_i \quad (3)$$

where
SWB_i – the change in the snow water balance in time step i [mm];
SWE_i – the snow water equivalent in time step i [mm];
SWE_{i-1} – the snow water equivalent in time step i-1 [mm].

This relationship assumes that information on how much snow cover remains during the transition from one time step to another is essential in defining the impact of the snow cover formation and its subsequent melting

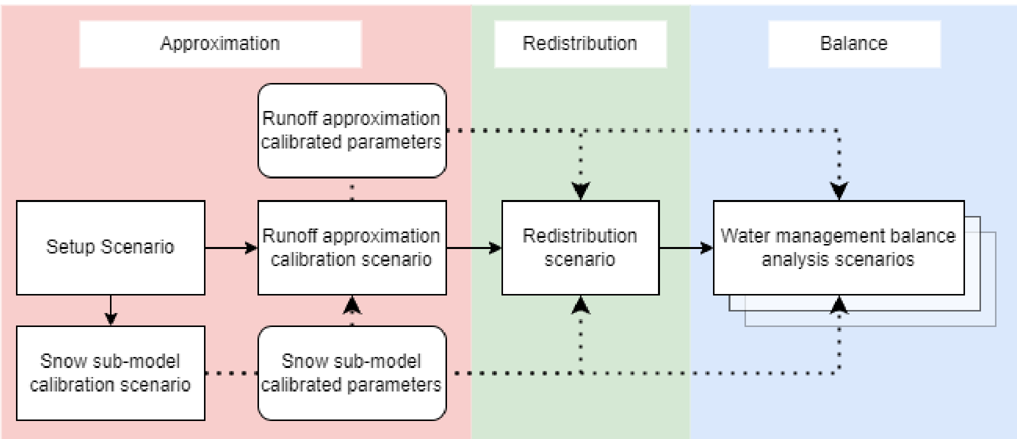

Fig. 1. Approximate Redistributive Balance model scenario branching.

over time. For example, with a monthly time step, the average monthly value is not important, but the value at the end of the month is. It follows from equation (3), that if the value of SWB is a negative value, it equals the accumulation of snow cover, while a positive value equals snowmelt.

Runoff approximation sub-model

Since the runoff approximation sub-model fulfills only an approximate role in the ARB model, it was possible to build it on simplified deterministic relationships. The individual variables were defined according to the simplified assumption that, except for the atmospheric components, the individual components of the hydrological cycle are interconnected and operate on the water balance principle in such a way that they decline/increase in order to maintain the water balance. The runoff approximation sub-model has five calibration parameters, with each sub-basin having its own set of parameters calibratable to the flow in the water gauge profile. Each variable in the model is affected by at least two other variables or calibration parameters.
In Healy (2010), the recharge, or, by Healy's definition, the drainage as well was defined by the general equation:

$$R = P - EA \tag{4}$$

where
R – the recharge [mm];
P – the precipitation [mm];
EA – the actual evapotranspiration [mm].

From equation (4), two representations of the potential recharge, i.e., RE_{pot} and C_{REpot} , were derived:

$$RE_{pot,i} = P_i + SWB_i - PET_i \tag{5}$$

and

$$C_{REpot,i} = \min\left(1, \max\left(0, \frac{(P_i + SWB_{,i} - PET_i)}{100}\right)\right) \tag{6}$$

where
$RE_{pot,i}$ – the potential recharge in time step i [mm];
$C_{REpot,i}$ – the coefficient of the potential recharge in time step i [-];
P_i – the precipitation in time step i [mm];
SWB_i – the change in snow water balance in time step i [mm];
PET – the potential evapotranspiration in time step i [mm].

The potential recharge quantifies the ratio between the atmospheric resources and demands in the form of an impact on the hydrological cycle, while the coefficient of the potential recharge serves as an indicator.
Fig. 2 shows a simplified form (without any input data) of the calculation cycle of the variables influencing the calculation of the total runoff. Each variable apart from the direct runoff is successively calculated with respect to the soil water capacity remaining from the previous time step and is then added to the calculation of the following variable. The calculation of the variables affecting the soil water capacity is therefore based on maintaining the water balance of the soil water capacity. The potential recharge serves as a counterweight that disturbs this balance, either towards a decrease or an increase in the soil water capacity.
The total runoff was divided into three parts: R_d as the direct runoff, R_s as the surface runoff, and R_{ss} as the sub-surface runoff. The variables themselves do not aim to precisely divide the parts of the runoff into separate components of the runoff but serve in a gradual sequence to approximate the amount of water that is available for the runoff from available sources. The calculation of the direct runoff is defined as:

$$if\ RE_{pot,i} > 0 \qquad then$$

$$R_{d,i} = RE_{pot,i}\left(\frac{(C_{REpot,i}\, C_{Rd} + C_r)}{(1 + C_{Rd})}\right) C_{Rd} \tag{7}$$

$$elseif\ RE_{pot,i} \le 0 \qquad then \qquad R_{d,i} = 0$$

where
$R_{d,i}$ – the direct runoff in time step i [mm];
C_r – the coefficient of the runoff [–];
C_{Rd} – the coefficient of the direct runoff (calibration range of the parameter used: $1 > C_{Rs} > 0$ [–]).

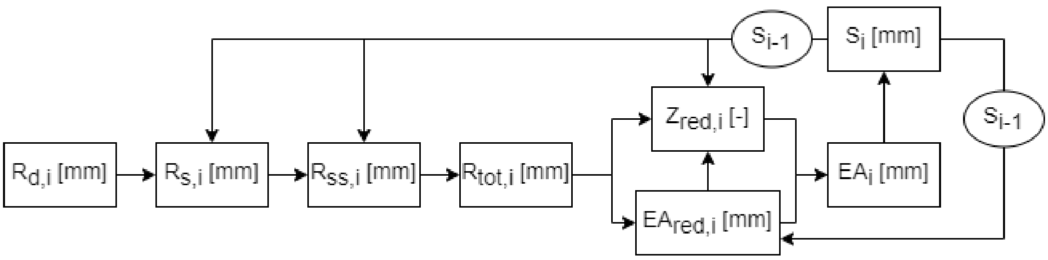

Fig. 2. Simplified order of the calculation of the runoff approximation sub-model variables ($R_{d,i}$ – direct runoff, $R_{s,i}$ – surface runoff, $R_{ss,i}$ – sub-surface runoff, $R_{tot,i}$ – total runoff, $EA_{red,i}$ – evapotranspiration reduction, $Z_{red,i}$ – relative value of the reduced soil water capacity, EA_i – actual evapotranspiration, S_i – soil water capacity in time step i, S_{i-1} – soil water capacity from time step i-1).

Direct runoff only occurs if the atmospheric sources (P, SWB) overweigh the requirements (PET). A calibratable parameter C_{Rd} was included in equation (7) so that the effect of the runoff coefficient on the direct runoff calculations was not reduced by changes in C_{Rd} as significantly as C_{REpot} was. The second part of the runoff could be described as surface runoff. The water supply in the soil is included in the calculation of this variable, while it no longer includes the runoff coefficient. The surface runoff is defined as:

$$if\ R_s < 0 \cap R_{pot} < 0 \qquad then \qquad R_{s,i} = 0$$

$$elseif\ RE_{pot,i} - R_{d,i} \le 0 \quad then$$
$$R_{s,i} = \left(S_{i-1} - \left(C_{REpot,i} + C_{Rs}\right)/2\, S_{max,i}\right) C_{REpot,i} \qquad (8)$$

$$elseif\ RE_{pot,i} - R_{d,i} > 0 \quad then$$
$$R_{s,i} = \Big(\left(RE_{pot,i} - R_{d,i} + S_{i-1}\right) - \left(C_{REpot,i} + C_{Rs}\right)/2\, S_{max,i}\Big) C_{REpot,i}$$

where
$R_{s,i}$ – the surface runoff in time step i [mm];
S_{i-1} – the soil water capacity from time step i-1 [mm];
$S_{max,i}$ – the maximum capacity of the soil water storage in time step i [mm];
C_{Rs} – the coefficient of the surface runoff (range of the calibration of the parameter used: $1 > C_{Rs} > 0.75$ [-]).

The sum of the potential recharge $RE_{pot,i}$ and the soil water capacity S_{i-1} from the time step i-1 and the subsequent subtraction of the direct runoff $R_{d,i}$ defines the water supply after the calculation of the direct runoff. By multiplying the maximum capacity of the soil water storage $S_{max,i}$ with the arithmetic mean between the coefficient of the potential recharge $C_{Repot,i}$ and the calibration parameter of the surface runoff C_{Rs}, it defines the amount of water that is, with respect to them, theoretically available from the water supply in the soil. The coefficient of the potential recharge $C_{REpot,i}$ serves here as a natural indicator of the need for availability of atmospheric water. The difference between these two sides multiplied by the coefficient of the potential recharge defines the amount of water that is available after calculating the direct runoff, but due to the high soil water capacity, it does not have enough space in the soil and must therefore also be part of the runoff.

Sub-surface runoff serves as the transition between a positive and negative potential recharge. As it is the only part of the runoff that is active when the potential recharge goes below zero, determining its boundaries is currently subject to change, as it is a decisive element in determining when a stream reaches the point of drying up. Currently, sub-surface runoff is defined as:

$$if\ RE_{pot,i} - R_{d,i} \le 0_{pot,i} \quad then$$
$$R_{ss,i} = \left(S_{i-1} - R_{s,i}\right) C_{Rss}\left(1 - \left|C_{REpot,i}\right|\right) \qquad (9)$$

$$elseif\ RE_{pot,i} - R_{d,i} > 0 \quad then$$
$$R_{ss,i} = \left(S_{i-1} + RE_{pot,i} - R_{d,i} - R_{s,i}\right) C_{Rss}\left(1 - \left|C_{REpot,i}\right|\right)$$

where
C_{Rss} – the coefficient of the sub-surface runoff (range of the calibration of the parameter used: $0.3 > C_{Rss} > 0$ [–]).

According to equation (9), the values of the sub-surface runoff will be at their maximum if the potential recharge is zero, and the soil water capacity from time step i-1, together with the potential recharge after subtracting the direct runoff and surface runoff, is reaching the maximum soil water capacity. The absolute value of C_{REpot} ensures a linear decrease until RE_{pot} reaches values of less than -100 mm or a value greater than 100 mm, at which point the sub-surface runoff reaches zero value. The calibratable parameter C_{Rss} defines how much of the water supply is available for the sub-surface runoff. The total runoff is calculated according to:

$$R_{tot,i} = R_{d,i} + R_{s,i} + R_{ss,i} \qquad (10)$$

where
$R_{tot,i}$ – the total runoff in time step i [mm].

The quantitative estimation of EA is, as in many general numerical codes, based on a comparison between the amount of available water and PET. If PET can be satisfied by the amount of available water, then EA is taken as PET; otherwise, EA is lower than PET and limited by the water available (Vázquez, 2003). Therefore, the amount of preserved water, by which the amount of water available from the soil water capacity will be reduced, is called the evapotranspiration reduction, and is calculated as:

$$EA_{red,i} = \min\Big(P + R_{sw}, \max\Big(0, C_{EA}S_{max} - \big(S_{i-1} + \max\left(0, R_{pot} - R_d\right) - R_s - R_{ss}\big)\Big)\Big) \qquad (11)$$

where
$EA_{red,i}$ – the evapotranspiration reduction in time step i [mm];
C_{EA} – the coefficient of the evapotranspiration (range of the calibration of the parameter used: $0.5 > C_{EA} > 0$ [-]).

The calibration parameter serves as a relative value of the water preserved. Subsequently, in the form of a relative value of the reduced soil water capacity, the water content in the soil, that is available for evapotranspiration is calculated. The reduced soil water capacity is defined as:

$$if\ RE_{pot,i} - R_{d,i} > 0 \qquad then$$
$$z_{red,i} = \frac{S_{i-1} + RE_{pot,i} - R_{d,i} - R_{s,i} - R_{ss,i} + EA_{red,i}}{S_{max,i}}$$

$$elseif\ RE_{pot,i} - R_{d,i} \le 0 \qquad then \qquad z_{red,i} = \frac{S_{i-1} - R_{s,i} - R_{ss,i} + EA_{red,i}}{S_{max,i}} \tag{12}$$

where
$Z_{red,i}$ –the reduced soil water capacity in time step i [mm].

The method used by (Delworth and Manabe, 1988) was integrated into the calculation of actual evapotranspiration, while the relative soil water capacity as variable z was replaced in this calculation by the reduced relative soil water capacity as z_{red}. The function "max(0, min(PET, P + SWB) -EA_{red})", which is subsequently added, ensures that at low values of z_{red}, the simultaneous exceedance of the PET value by the sum of P and SWB does not cause a sharp increase in EA:

$$EA_i = \min\left(PET_i, \max\left(0, \min\left(PET_i, P_i + SWB_{,i}\right) - EA_{red,i}\right) + \ if\left(z_{red,i} < 0.75, \frac{z_{red}{}^2 S_{max}}{0.75}, z_{red}{}^2 S_{max}\right)\right) \tag{13}$$

The equation to calculate the value of the soil water capacity at the end of the time step is:

$$S_i = S_{i-1} + P_i + SWB_i - R_{tot,i} - EA_i \tag{14}$$

Thanks to the calculation method used, the variables R_{tot} and EA maintain the value of S_i in the range (0, S_{max}) without using the min/max functions in the equation of S_i. By observing the behavior of the variables during modeling, they show an asymptotic bound to the range (0, S_{max}) while the S_i values balance within this range, which provides a more realistic approach to the data range (de Figueiredo et al., 2021).
In order to calculate the cycle, it is necessary to determine the definition of the maximum capacity of the soil water storage S_{max}, whose effect on the relationship with the soil moisture is barely described in the literature (Demirel et al., 2019; Zhuo and Han, 2016). The soil water storage capacity may present a wide range of spatial variations, depending on the soil and crop characteristics (Hillel, 2003); they are also important to include in the calculation of S_{max}, since it is possible to smooth out the different proportions of the individual micro-basins. Regarding the current variables, the number of which was not intended to be expanded, the best variable, considering both the soil and the crop characteristics to some degree, was the runoff coefficient. For the purpose of evaluating how capable a micro-basin is in absorbing and maintaining water in the soil, instead of the runoff coefficient, it was more appropriate to use the infiltration coefficient, which, according to Suryoputro et al. (2017) is:

$$C_i = 1 - C_r \tag{15}$$

where
C_i – the coefficient of infiltration in time step i [–].

Incorporating temporal variability into the calculation of S_{max} was a matter of rough estimation due to the limitations of the input data, while the averaged values of the vegetation coefficient K_v were used based on the table of monthly K_v (for Grass Reference Evapotranspiration) from the monthly vegetation evapotranspiration observed for different types of vegetation and site conditions (Howes et al., 2015), see Table 1.
When combining the infiltration coefficient with the vegetation coefficient, the maximum capacity of the soil water storage is defined as:

$$S_{max,i} = K_{v,i}(t) C_i C_{Smax} \tag{16}$$

where
$S_{max,i}$ – the maximum capacity of the soil water storage in time step i [mm];
$K_{v,i}(t)$ – the vegetation coefficient in time step i; when the month t = 1, 2 … 12) [mm];
C_{Smax} – the coefficient of the maximum capacity of soil water storage (range of the calibration of the parameter used: $100 < C_{Smax} < 1000$ [mm]).

Because the runoff approximation sub-model ignores the effect of the interaction with the groundwater, the values of S_{max} tend to be higher than in models that do take the groundwater into account.

Redistribution sub-model

The redistribution sub-model is represented as a scenario following the runoff approximation scenario. It does not require any calibration, but the precalculated variables in the data structure, which are required for the redistribution sub-model, are calculated for every micro-basin, and each micro-basin is dependent on the summarized variables of all the micro-basins in the sub-basin to which they belong. The enforced recalculation of one of those variables in one micro-basin by the user requires all the dependent variables of the micro-basins subordinated to the sub-basin to be automatically recalculated, thereby significantly increasing the computational time required to recalculate these variables in the data structure of the WEAP model, thus making it difficult to analyze them effectively in real-time. On the other hand, the recalculation of the results is not affected because all the variables in the scenario are recalculated during the process anyway. The outflow volume from the micro-basin equation is in the form:

$$V_{MB,i\,(j)} = R_{tot,i}\ A_{MB(j)}\ 10^3 \tag{17}$$

where
$V_{MB,i(j)}$ – the outflow volume from micro-basin j in time step i [m^3];
$A_{MB(j)}$ – the micro-basin area [km^2].

In WEAP, the variable with which it is possible to define the outflow from the node on the modeled stream is called the Surface Water Inflow (SWI). To calculate it from the outflow volume of the micro-basin, the form of the equation is:

$$SWI_i = V_{MB,i(j)}/(86400\, nDays_i) \tag{18}$$

where
SWI_i – the surface water inflow in time step i [$m^3\ s^{-1}$];
86 400 – the number of seconds in a day [–];
$nDays_i$ – the number of days in time step i [–].

The *nDays* variable is represented via the "Days" function in WEAP. To be able to calculate the difference between the cleansed outflow from the sub-basin from equation (1) and the volume of runoff from the micro-basins subordinated to the sub-basin, it is necessary to summarize them with the equation:

$$V_{SB,i} = \sum_{j=1}^{n} V_{MB,i(j)} \tag{19}$$

where
$V_{SB,i}$ – the outflow volume from the sub-basin in time step i [m^3];
n – the number of micro-basins in the sub-basin [–];
$V_{MB,i(j)}$ – the outflow volume from micro-basin j in time step i [m^3].

Subsequently, the difference in the outflow volume is defined by the equation:

$$V_{d,i} = Q_{c,i}\, 86400\, nDays_i - V_{SB,i} \tag{20}$$

where
$V_{d,i}$ – the difference in the outflow volume [m^3];
$Q_{c,i}$ – the cleansed outflow from the sub-basin in time step i [$m^3\ s^{-1}$].

The positive value of the difference in the outflow volume means that the runoff approximation sub-model in the current time step produces less water than it should according to the cleansed outflow, while the negative value means the opposite. Therefore, the positive value of V_d needs to be additionally distributed into the nodes of the micro-basins, while in the case of a negative value, the outflow from the nodes of the micro-basins should be reduced by the absolute value of negative V_d, with respect to the same redistribution pattern as for a positive V_d. For the spatial variability between the micro-basins, the infiltration coefficient calculated according to equation (15) was used at the initial point of defining the model. According to this equation, the calculation based on the runoff coefficient define the distribution of water sources only between the runoff and infiltration, while in fact the calculated coefficient also includes the evapotranspiration coefficient. Therefore, using the trial-and-error method, an equation defining the approximate value of the infiltration (and therefore also the evapotranspiration) coefficient based on the runoff coefficient was created. The equation fits the ratio between the runoff, infiltration, and evapotranspiration in the annual water balance for humid and sub-tropical regions (Keszeliová et al., 2021; Olofintoye et al., 2022), but it is a struggle to adapt it to semi-arid regions (Yaykiran et al., 2019), as the relationship between PET and P is not yet incorporated into the equation:

$$C_{inf} = \max(0, (C_r + \log((1 - C_r)/C_r))/2) \tag{21}$$

The redistributive share of the micro-basin is calculated from C_{inf} and the area of the micro-basin as:

$$C_{red} = C_{inf}\, A \tag{22}$$

where
C_{red} – the redistribution share of the micro-basin [km^2];
A – the area of the micro-basin [km^2].

Subsequently, C_{red} is then summarized for all the micro-basins in the sub-basin as:

$$C_{red,SB} = \sum_{j=1}^{n} C_{red,MB(j)} \tag{23}$$

where
$C_{red,SB}$ – the summarized redistribution coefficients of the micro-basins in sub-basin [m^3];
n – the number of micro-basins in the sub-basin [-];
$C_{red,MB(j)}$ – the redistribution coefficient of the micro-basin j [m^3].

For redistribution purposes, predefined WEAP variables, the Groundwater Inflow Volume (GIV) and the Groundwater Outflow Volume (GOV) are used to equalize the simulated and measured outflows from the sub-basin. To function correctly, these variables need to be connected to the groundwater node; therefore, for each sub-basin, a groundwater node is created with a sufficient volume of water. In this stage of the development of the model, the use of these features of the model has nothing to do with modeling groundwater, although it is part of the plan for possible future integration.

$$\begin{aligned} &if \quad V_{d,i} > 0 \quad then\ GIV_i = V_{d,i} \frac{C_{red,MB(j)}}{C_{red,SB}} \\ &elseif\ V_{d,i} < 0 \quad then\ GIV_i = 0 \end{aligned} \tag{24}$$

$$\begin{aligned} &if \quad V_{d,i} < 0 \ \ then\ GOV_i = \left| V_{d,i} \frac{C_{red,MB(j)}}{C_{red,SB}} \right| \\ &elseif\ V_{d,i} > 0 \ \ then\ GOV_i = 0 \end{aligned} \tag{25}$$

where
GIV_i – the groundwater inflow volume in time step i [m^3];
GOV_i – the groundwater outflow volume in time step i [m^3].

Data

The WEAP software calculates the change in the flowrate in the nodes created in the scheme; therefore, the nodes were created in the streams at each kilometer of their length, for which the outflow areas called micro-basins were delineated. The areas of the individual micro-basins of the basin modeled range from 48 km^2 to 0.01 km^2 with a median value of 1.447 km^2; and the altitude ranges from 103 m a.s.l. up to 822 m a.s.l. Fig. 3 shows the location of the lower Hron river basin. The variables defining both the snow sub-model and runoff approximation sub-model are calculated for every micro-basin in the basin modeled. Each sub-basin has a set of the same calibration parameters for its corresponding micro-basins.
As to validating the ARB model, two sub-basins of the water gauging station (WGS), were separately modeled. As seen in Fig. 3, the WGS 7310 sub-basin served as the first calibration sub-basin, while WGS 7308 was the validation station within it. The second sub-basin of WGS 7335 was used, as it has WGS 7318 within its area. Because the second's sub-basin's boundaries were delineated by the water gauging stations selected for the purpose of the whole model of the lower Hron River, the runoff from the WGS 7335 sub-basin was calculated according to equation (2) by subtracting the inflow into the sub-basin. In the case of the first sub-basin, the outflow from the sub-catchment was equal to the flow in WGS 7310.
WGS 7335 is located on the main Hron River catchment, while the validation WGS 7318 is situated on its tributary the Lužianka. WGS 7310 is located on a tributary of the Hron River called the Sikenica; and its validation WGS 7308 is similarly located on

Table 1. The averaged values of the vegetation coefficient for incorporating an estimation of the temporal variability into S_{max} calculations

Month	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
K_v [–]	0.62	0.62	0.66	0.72	0.85	0.92	0.98	0.95	0.86	0.84	0.78	0.70

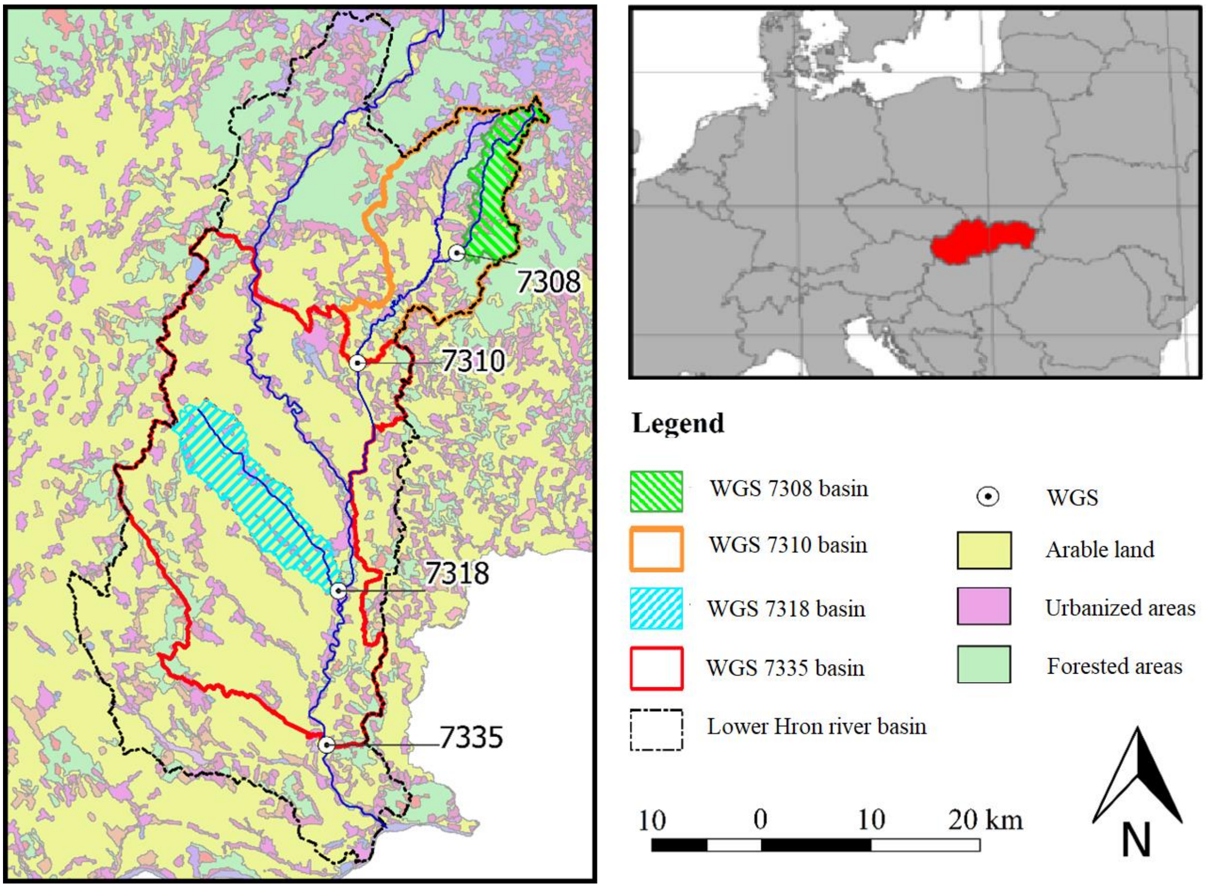

Fig. 3. Sub-basins of the calibration and validation water gauging stations (WGS) in the basin of the lower Hron River.

a tributary of the Sikenica called the Jablonovka. Both the first and second sub-basins therefore have their validation WGS located beside the main river of the sub-basin, thereby adding strength to the validation of the accuracy of the model.

The input data, as described in Tables 2 and 3, can be divided between the sub-basins and micro-basins. The time series of the hydrometeorological data in the period 2007–2019 was selected for the approximate redistributive balance modelling to estimate the distribution of the water resources. Point data from measuring stations for the temperature (14 stations) and precipitation (45 stations) were input for IDW and conventional kriging methods, used to create the raster data, from which a time series of the average values was subsequently created using zonal statistics for the individual micro-basins. All the hydrological variables calculated within the micro-basins, such as runoff or evapotranspiration, were represented as a water column in millimeters. In the case of the runoff coefficient and average altitude, the raster input data was also processed using zonal statistics. The calculation of the runoff coefficient was based on the tabular processing of the linear dependence on the slope, land use, and soil types (Mahmoud and Alazba, 2015). The total potential monthly evapotranspiration was aggregated from the total daily potential evapotranspiration, which was estimated according to the Blaney-Criddle empirical method (Schrödter, 1985).

Table 2. **Input data used for calculation of the sub-basin variables: Slovak Hydrometeorological Institute (SHMÚ), Slovak Water Management Enterprise (SVP)**

Input data	Precalculated from	Source	Measurement	Data application
Streamflow [$m^3 s^{-1}$]		SHMÚ	Stations	Redist. sub-model
The abundance of springs [$m^3 s^{-1}$]		SHMÚ	Stations	Redist. sub-model
Surface water withdrawals [m^3]		SHMÚ	Reporting	Redist. sub-model
Wastewater discharges [m^3]		SHMÚ	Reporting	Redist. sub-model
Water diversions [$m^3 s^{-1}$]		SHMÚ	Reporting	Redist. sub-model
Manipulation of the volume of reservoirs [$m^3 s^{-1}$]	Water level elevation [m a.s.l.] Volume-elevation curve [–]	SVP	Monitoring Documentation	Redist. sub-model

Table 3. **Input data used for calculation of the micro-basin variables: Slovak Hydrometeorological Institute (SHMÚ), Geodetic and Cartographic Institute Bratislava (GKÚ), State Geological Institute of Dionýz Štúr (GÚDŠ), digital elevation model (DEM), airborne laser scanning (ALS), S_d - the potential length of sunlight during the day [h], S_y – the length of the average annual amount of potential sunlight during the day [h]**

Input data	Precalculated from	Source	Measurement	Data application
Monthly average temperature [°C]	Daily average temperature	SHMÚ	Stations	Snow sub-model
Average temperature in the last week of the month [°C]	Daily average temperature	SHMÚ	Stations	Snow sub-model
Total monthly precipitation [mm]	Total daily precipitation	SHMÚ	Stations	Snow sub-model
Average altitude [m a.s.l.]	DEM 1x1 [m]	GKÚ	ALS	Snow sub-model/Runoff approx. sub-model
Monthly total potential evapotranspiration [mm]	Daily average temperature	SHMÚ	Stations	Snow sub-model
	S_d (DEM 1x1 [m])	GKÚ	ALS	Runoff approx. sub-model
	S_y (DEM 1x1 [m])	GKÚ	ALS	Runoff approx. sub-model
Coefficient of runoff [–]	Slope (DEM 1x1 [m])	GKÚ	ALS	Runoff approx. sub-model/Redist. sub-model
	Soil type	GÚDŠ	GIS	
	Land use	Author	Delineation	

Results

The performance of the ARB model was visually assessed using the correlations between the observed and simulated outflows (see Fig. 4–5). The left side of Fig. 4 shows the ability of the redistributive model to equalize the inequalities between the approximated and observed outflows. The right side of Fig. 4 shows how with a sufficiently good approximation, the redistributive sub-model can simulate runoff even on tributaries above the standard, if the sub-basin is homogeneous to some extent, which can also be evaluated according to the similarity of the flows modeled in the sub-basin.
On the right side of Fig. 5, the blue dots representing the runoff approximation sub-model outflow values show a general overestimation, while the red dots in the redistribution process lead to a more precise, yet opposing underestimation of the outflows.

To evaluate the performance of the model, the Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE), and Pearson's correlation coefficient (*r*) between observed and simulated outflows were also calculated (see Table 4). The performance of the runoff approximation sub-model was significantly better in the first sub-basin, while the second sub-basin could not simulate the trends in the flow regime at either the validation or the calibration station.
From October to March, the mostly higher approximated long-term average monthly outflows compared to the observed data can be seen in Table 5, especially for the second sub-basin. The opposing trend can be observed from April to September, which can be identified as the result of calibration of the parameters during the approximation of the runoff i.e., the effort to even out inaccuracies during the winter months.

First sub-basin tested: Calibration – WGS 7310; Validation – WGS 7308

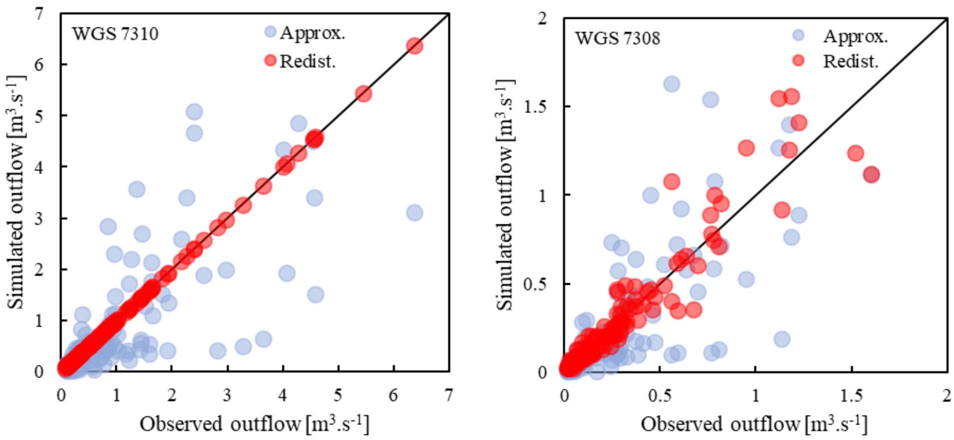

Fig. 4. The correlation between the observed and simulated outflows for the first sub-basin tested: Approximation (Approx. – blue dots) and redistribution (Redist. – red dots) scenarios.

Second sub-basin tested: Calibration – WGS 7335; Validation – WGS 7318

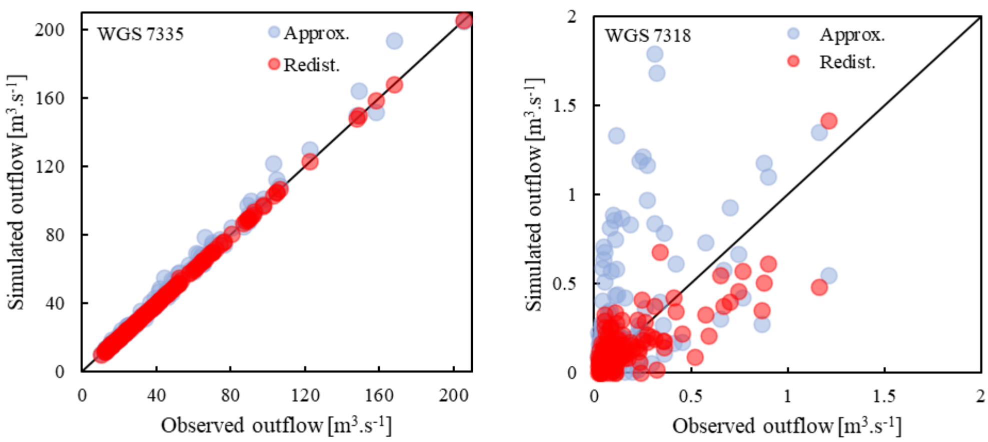

Fig. 5. The correlation between the observed and simulated outflows for the second sub-basin tested: Approximation (Approx. – blue dots) and redistribution (Redist. – red dots) scenarios.

Table 4. The ARB model performance statistics in time period 2007–2019 (time steps – 156 months) for the first and second sub-basins tested

Characteristics	Sub-basins							
	1st sub-basins tested				2nd sub-basins tested			
No. WGS	7308		7310		7318		7335	
Area [km^2]	50.1		164.1		92.2		651.8	
Scenario	Approx.	Redist.	Approx.	Redist.	Approx.	Redist.	Approx.	Redist.
NSE [–]	0.48	0.89	0.42	1	-3	0.59	-9.1	1
MAE [m^3 s^{-1}]	0.12	0.052	0.45	0.00081	0.24	0.09	2	0.079
r [–]	0.78	0.95	0.75	1	0.49	0.77	0.24	1

Table 5. Long-term average monthly outflows for first and second tested sub-basins

Tested	No. WGS	Scenario	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1st sub-basins	7308	Observ.	0.275	0.487	0.560	0.369	0.246	0.164	0.059	0.087	0.094	0.100	0.206	0.335
		Approx.	0.326	0.546	0.645	0.226	0.103	0.093	0.053	0.042	0.172	0.113	0.204	0.219
		Redistr.	0.286	0.572	0.513	0.394	0.210	0.194	0.067	0.096	0.156	0.107	0.202	0.286
	7310	Observ.	0.975	2.006	1.731	1.274	0.778	0.712	0.249	0.371	0.478	0.390	0.798	1.122
		Approx.	1.144	1.899	2.276	0.593	0.343	0.299	0.189	0.152	0.541	0.409	0.804	0.845
		Redistr.	0.977	2.007	1.731	1.274	0.778	0.712	0.249	0.371	0.478	0.386	0.797	1.122
2nd sub-basins	7318	Observ.	0.174	0.241	0.239	0.217	0.166	0.197	0.093	0.104	0.114	0.127	0.135	0.171
		Approx.	0.656	1.000	0.739	0.194	0.139	0.088	0.106	0.076	0.171	0.190	0.263	0.443
		Redistr.	0.155	0.163	0.229	0.179	0.153	0.218	0.085	0.104	0.091	0.129	0.155	0.148
	7335	Observ.	1.616	1.576	1.819	1.455	1.288	1.766	0.644	0.770	0.614	0.912	1.173	1.390
		Approx.	5.631	8.366	5.909	1.528	1.147	0.710	0.803	0.578	1.287	1.526	2.026	3.732
		Redistr.	1.571	1.596	1.790	1.402	1.243	1.758	0.667	0.782	0.647	1.112	1.238	1.383

Discussion

The right side of Fig. 6 interprets how much water had to be distributed via the redistribution model to equalize the simulated and measured streamflow. The increasing value indicates that the runoff approximation sub-model overestimated, while the decreasing value indicates the opposite; the graph thus serves as an indicator of the accuracy of the runoff approximating the sub-model. Therefore, a prerequisite for satisfaction with the simulation of the runoff approximation sub-model could be the condition that the variable ΔVd fluctuates around its initial value. The low degree of precision in the second sub-basin approximation has several causes (as set out in the results). They all come from the difference between the sub-basin conditions of the validation and calibration stations. The difference between their sub-basins lies not only in the significant difference in the area and runoff (compared to the first sub-basin), but the Hron River, on which WGS 7335 is located, also crosses the gravely alluvium of the lower Hron along the entire length of the sub-basin of WGS 7335, and thus is significantly more affected by the interaction with groundwater than the other streams that flow into the Hron River in this area.

Since the conceptual snow sub-model used can also be responsible for significant deviations in the runoff approximating sub-model during the winter season, the statistical parameters of the simulation in Table 6 are evaluated in the range of the month May – October (summer season without the influence of snow). While the evaluation of only the summer months showed a significant improvement in the second sub-basin, thereby indicating the significant effect of the inaccuracy of the snow sub-model, in the case of the first sub-basin, the statistical parameters show a slight deterioration, which can be represented in this case as the slightly better results of the snow sub-model rather than the runoff approximation sub-model.

The issue which, at this spatial scale in a monthly time step that any modeling of snow water equivalent would face, is the fact that precipitation is not equally distributed during a month. Another explanation could be that the snow water equivalent data observed in the weekly time step, which were used in the snow sub-model calibrations, are not efficient for this sub-basin scale. Therefore, the snow sub-model's degree of inaccuracy would be better solved via evaluating it on a weekly or even daily time step, either externally or in a separate model created in WEAP using a more detailed time step. When trying to use the ARB model in any analysis of the future scenarios, it would be necessary to transform time-invariant inputs such as land use into the variables in the form of scenarios (see Kohnová et al., 2019).

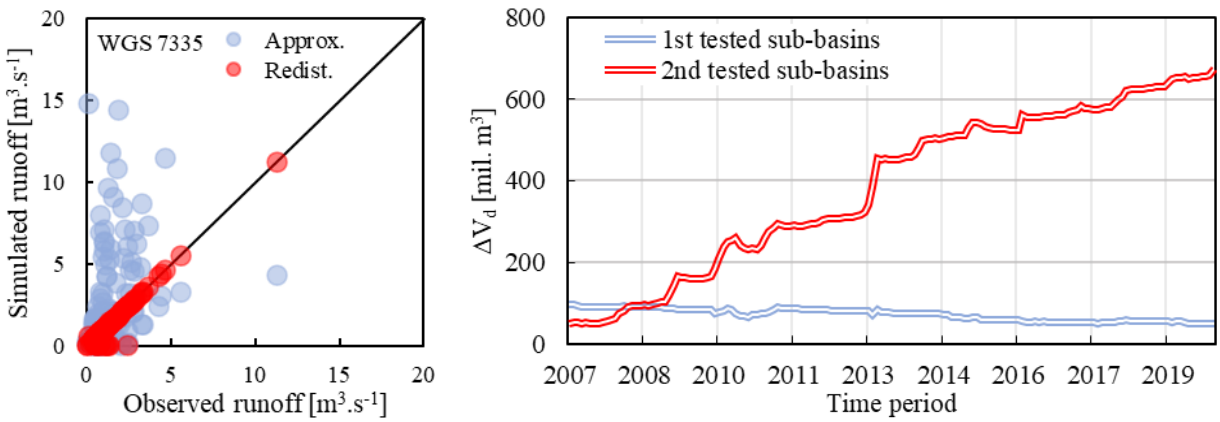

Fig. 6. The correlation between the observed and simulated runoff for WGS 7335: Approximation (Approx. – blue dots), redistribution (Redist. – red dots) scenario (left), and cumulative outflow volume difference of redistribution sub-model for the first and second sub-basins tested (right).

Table 6. The ARB model performance statistics in time period 2007–2019 (time steps – 156 months) for the first and second sub-basins tested

Sub-basin	1st tested sub-basins				2nd tested sub-basins			
Scenario	WGS 7308		WGS 7310		WGS 7318		WGS 7335	
	Approx.	Redist.	Approx.	Redist.	Approx.	Redist.	Approx.	Redist.
NSE [–]	-0.02	0.79	0.25	1	0.53	0.8	0.32	1
MAE [m^3 s^{-1}]	0.077	0.037	0.29	0.00074	0.094	0.062	0.79	0.066
r [–]	0.52	0.92	0.58	1	0.74	0.89	0.58	1

Conclusion

The ARB model was created as the gradual result of a vision of accurate modeling in the field of retrospective analysis of the quantitative water management balance of flows, which in Slovakia focuses more on the evaluation of the quantity of the outflow from smaller tributaries, which lack continual measurement equipment.
The results indicate that the validation water gauging stations show a relatively high degree of precision of the simulation in the redistribution scenario; however, the simulation of sub-basins affected more by groundwater will also require more attention to detail, as will the conceptual snow sub-model. Although the ARB model uses an unconventional method, it provides the expected and satisfactory results. The research on the model will be followed by testing the model on a weekly time step and creating the concept of scenarios for an analysis of the impact of water management on the water balance to fulfill the balance part of the ARB model.

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Ing. Miroslav Kandera (*corresponding author, e-mail: miroslav.kandera@stuba.sk)
Assoc. Prof. Ing. Roman Výleta, PhD.
Department of Land and Water Resources Management
Faculty of Civil Engineering
Slovak University of Technology in Bratislava
Radlinského 11
810 05 Bratislava
Slovak Republic