Application of the Water Evaluation And Planning (WEAP) Model to Quantitative Water Balance Modelling in the Upper Hron River Basin (Slovakia)

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Abstract. The assessment of water resources and the availability of water in a river basin is one of the main tasks enabling efficient water management. Recent developments in the computer industry and information technology allow us to create powerful computer systems for solving water management balances. Their advantage is in their ability to solve variations with the help of computers, both in the sources and in the water requirements. In Slovakia, at present, the individual elements of the water management balance are divided and evaluated separately, i.e., into the surface and groundwater, and these are further divided into a quantitative and a qualitative component. The paper aims to model the retrospective quantitative water management balance of surface waters using the Water Evaluation and Planning (WEAP) simulation balance software. The water management balance of surface waters is evaluated in a monthly time step in selected profiles in the Hron River basin for the period 2010 - 2015. The data input to the model were flows, abstractions, discharges, and manipulations of reservoirs. The paper is focused on the functionality of the WEAP simulation model with respect to the implementation of the current methodology of water management balances in Slovakia, both in terms of the details of the information input and their amount and also in the time required for their preparation and compatibility. We show that the software does not require very detailed input data and offers an integrated approach to solving various problems in the management of water resources. The WEAP software has a user-friendly graphic user interface (GUI) that provides the ability to present and interpret results in the form of tables and graphs. Its application in a selected pilot river basin showed that it could be an easy-to-use model building tool for optimal and successful development, planning and forecasting in water management and the knowledge of water redistribution in space and over time in Slovakia.

1. Introduction
The basis of the water management policy of Slovakia is the idea of the sustainable use of water resources. The administrator and operator of the country's water management must take into account the natural variability of water resources over time and in space, their sustainability, and their degree of security. The definition of a quantitative water balance is a comparison of water resources with water requirements over time and in space. Its purpose is to assess the interactive elements of the water management balance and evaluate whether, when, and where the water requirements will not be met. This primary relationship about inequality is rarely applicable in this form, see Figure 1 [1]. To express the actual situation, it is also necessary to take into account all the types of the elements of this inequality
i.e., natural water resources, water abstractions, water discharges, the impact of reservoirs, water transfers, and the minimum required flow [2].

![Diagram](image)

**Figure 1.** The universal relationship concerning inequality in water management in Slovakia

Water transfers and the activity of a reservoir do not have a precise classification in this relationship. They are determined with regard to their status over time, which affects the complexity of the balance assessment. Together with the need to analyze the variability of water resources, these factors are the impetus for the application of simulation software in the water balance of Slovakia. Worldwide, the simulation software for water management balance are tools for modelling complicated aquatic environments, whether for deciding on the redistribution of limited water resources or on their analysis and balance. While the basis of these models is the same, their development always directs the given model to focus on specific tasks.

Much software has been created thus far to address water management and water redistribution in a river basin. Software such as RIBASIM, MIKE Basin and WEAP have undergone the most significant development and both are the most often used in practice worldwide [see e.g., 3-7]. Over the years, these software tools have developed their so-called genericity, i.e., a set of features that software of this kind have in common. This applies not only to the calculation method, the creation of data or the schematic structure of a river basin and river network, but also to the characteristics and form of the user environment that was specified for each software when it was created and that this common genericity subsequently reinforces. Due to the mentioned genericity of software developed to solve water balance issues, the selection of a specific software without testing it and its properties is a complex question, which is exacerbated by the fact that the methodology of the water management balance in Slovakia significantly differs from the methods of solving the redistribution of water within the water management of the countries where they were developed and by the fact that they have not been fully tested in Slovakia.

The basis of this paper is to evaluate a retrospective quantitative water management balance of surface waters using the Water Evaluation and Planning (WEAP) software, while the aim is to emphasize the preservation of the established methodology of the Water Management Balance of Surface Waters in Slovakia. This includes the ability to model different flows and the balance condition in specified balance profiles in a monthly time step in the Hron River basin for the period 2010 - 2015. The WEAP software has not been used in Slovakia thus far; therefore, the authors aim to evaluate its possibilities for application in our geographical conditions. Our efforts have mainly been devoted to creating the most time-efficient way to build and prepare a model; we did not intend to examine all the features and capabilities of the software.

2. Material and methods

As part of monitoring the status of surface water, there is a relatively dense network of streamflow gauges and weather stations in Slovakia; a large amount of the water use is also monitored. There are 26 streamflow gauges in the upper Hron River basin itself, when considered from its source up to the profile of Banská Bystrica, with an area of 1,763 km². The study area is located in the center of Slovakia, at an altitude of 334 – 2007 m a.s.l. (Figure 2). In the six-year range from 2010 to 2015, which is modelled in a monthly step, 24 surface water abstractions, 25 groundwater abstractions, and 47
wastewater discharges were active in the given area. This data were the data input of the WEAP software.

![Location map of the Hron River basin](image)

**Figure 2.** Location map of the Hron River basin: streamflow gauges (blue points), wastewater discharges (yellow points), groundwater abstraction (dark red points) and surface water abstractions (red points)

2.1. Computation of the water balance

The solution of the water balance has an inconsistent form on a global scale, not only in terms of the time step in which it is addressed in various countries or in its methodology, but in the very principles that individual countries apply to water management. In Slovakia, water balance computations are performed in specified balance profiles for the months of a calendar year. The balance condition is the result of comparing the flows cleared of manipulation with the minimum required flows, thus solving the basic equation of the water balance. The minimum required flow is compared with the cleaned flow. The form of the relationship in the developed form appears as [8]:

\[
BSC = \frac{E - X \pm N \pm P}{MQ - X}
\]

(1)

where:
- \(BSC\) - value of balance condition [-],
- \(E\) - affected flows [m\(^3\)/s],
- \(N\) - changes in the volume of water in the reservoir [m\(^3\)/s],
- \(P\) - water transfer values [m\(^3\)/s],
- \(MQ\) - minimum required flow [m\(^3\)/s],
- \(X\) - impact on the flow of water users [m\(^3\)/s].

Based on the calculated BSC values, the balance condition in Slovakia is determined in a monthly time step in categories A, B, and C according to Table 1.
Table 1. Categories of balance condition.

| Category | Balance condition | BSC Range [-] |
|----------|-------------------|---------------|
| A        | Active            | > 1.1         |
| B        | Tense             | 0.9 to 1.1    |
| C        | Passive           | ≤ 0.9         |

2.2. WEAP modelling procedure

The Water Evaluation and Planning (WEAP) software, which was developed in 1988 and is supported by the Stockholm Environment Institute (SEI), is a tool for integrated water resource planning. It provides a comprehensive, flexible, and user-friendly framework for water and environmental policy analysis [9]. In principle, its three functions need to be highlighted:

- Water balance database: WEAP provides a system for maintaining and processing information on water discharges and abstractions,
- Scenario generation tool: simulates water demand, supply, outflow, flow, storage volume, pollution generation, purification and discharge, and water quality,
- Strategy Analysis Tool: WEAP assesses a range of options for water development and management, taking into account the diverse and conflicting uses of water systems.

WEAP is a software for examining alternative water development and management strategies. The quantitative estimations of the availability of water, water demands, and water consumption, both on a temporal and on a spatial scale, can be supported by modelling tools capable of simulating the hydrological processes and water management practices at a catchment level for the current status, as well as for various alternative scenarios [10].

As already mentioned, each balance model, despite its general genericity, has its unique features and focus. In combination with the need to model within the framework of a predetermined methodology of the processing and evaluation of the water management balance, this fact can result in various pitfalls and complications, primarily when modelled with previously unused software. Other steps, therefore, supplement the procedure of creating a scheme, filling it with data, and calibrating the whole model. In particular, there is an incompatibility between the possibilities and capabilities of the software and the methodology of the water management balance and the search for a way to model with the software as quickly and efficiently as possible.

In addition to the preservation of the established methodology of the Water Management Balance of Surface Waters in Slovakia, another requirement was to use simple hydrological modelling to extend the balance assessment from the balance profiles to the entire length of the modelled flows. Since WEAP is a 0-dimensional model, i.e., it only calculates at points created in the scheme; this requirement was met in a way that points were created at streams in every kilometre of the length to which the flow was calculated based on their share in the river basin area. Due to the large number of modelled structures, it was necessary to automate their modelling, especially the river network. While the creation of point objects as well as transmission links can be automated in the scheme utilizing integrated scripts, the model currently does not have an integrated tool for the automatic creation or import of a river network.

2.2.1. Schematization of the Hron River basin in the WEAP software

The graphic user interface of WEAP includes five main views: Schematic, Data, Results, Scenario Explorer and Notes. Manual creation of the schematization is performed in the Schematic part. Currently, with a focus on maximum automation, the only objects needed to be created manually are rivers. The creation of rivers can be partially automated. In the first step, they need to be manually created in WEAP, but only their simple geometrical representation (at least one line has to be created).
After their creation, a shapefile of the polyline objects is saved in the folder of a certain model (see WEAPArc.shp). In the second step, it can be modified using GIS software by replacing the geometry of these objects with the geometry of the underlying layer representing streams. At present, all the layers must be in the WGS 84 reference coordinate system. Creating point objects can be done by executing the list of scripts in a scripting section, which is located on the top bar (Advanced >> Scripting >> Edit Scripts). All the objects share the same form of the script. A detailed description is in the WEAP user guide [11].

The study area was divided into sub-catchments for the needs of modelling simple hydrology, one for each streamflow gauge. The streamflow was generated by adjusting the rainfall to the streamflow data at the gauges, which is done by calculating the runoff coefficient, including the water use and manipulation, according to:

\[
C = \frac{\Delta Q - X}{AP}
\]

where:
- \(C\) – runoff coefficient [m³/month],
- \(\Delta Q\) – difference between streamflow at outflow gauge and inflow gauges [m³/month],
- \(X\) - impact on the flow by water users [m³/month],
- \(A\) – drainage area of the streamflow gauge [m²/month],
- \(P\) – total precipitation [m³/month].

![Figure 3. Schematic view of the streamflow distribution in the drainage areas of the streamflow gauges; streamflow gauges (blue circle), demand sites (red circle), catchment nodes (green circle), wastewater discharges (green rectangle), tributary inflow nodes (blue circle).](image)

The streamflow is then calculated in the catchment node by multiplying the runoff coefficient by the total precipitation and distributing it to the tributary inflow nodes created at every river (Figure 3). The nodes share a portion of the streamflow based on their share of the area of the drainage area of the streamflow gauge.
3. Results and discussion

Because of the method used to calculate the streamflow, the difference between the calculated and observed streamflows should be zero. However, there were differences at the Bystrianka creek, a tributary of the river Hron, over three months (see Figure 4). As there are two streamflow gauges at Bystrianka, the average monthly flow observed was higher at the upper gauge in those months. Whether it is the outflow to the groundwater or unreported withdrawals, the solution may determine the outflow to the groundwater as a negative difference between the upper and specific gauges.

![Figure 4. Modeling of relative-to-observed streamflow at the gauges](image)

The streamflow calculated can be displayed in a downstream graph. While the nodes shown on the graph can be filtered so that important nodes can be part of the graph, there is no control over which node labels will be visible on the exported graph. In Figure 5, there is an apparent significant increase in the flow below river kilometer 213, which is caused by the inflow of the Čierny Hron River, the label of which was not visible on the X-axis. Although there is a graph manager at the result section of WEAP, where every element of the graph can be eventually edited, it should be considered outdated, and a more sophisticated user interface is required.

![Figure 5. Annual streamflow on the Hron River for the affected flow (blue line) and the minimal required flow (red line)](image)

Thanks to the software’s ability to compare the selected scenarios with other ones, the balanced condition of the river can be shown by comparing the affected flows with the minimum required flows,
following equation (1). In this way, the balance condition can be shown for the whole time series at a certain point. In the catchment, the tensest balance conditions were observed at the tributary of the Hron River, Bystrica.

Figure 6 demonstrates the balance condition on the streamflow gauge, which is two kilometers upstream from the Bystrica inflow to the Hron, where the evaluation point of the balance condition is. The poorest balance condition was in September 2012 with a value of 0.78, which, according to Table 1, is considered a passive balance condition. The time step with the lowest balance condition can be shown on the downstream graph, similarly to Figure 5.

Figure 6. Balance condition at the streamflow gauge on the Bystrica River, period 2012-2015

Figure 7 shows the visible low balance condition from the head flow until the inflow of the Harmance. The main reason for that is the same conditions of the streamflow distribution for both scenarios. As the minimum required flow was defined for the streamflow gauges, its distribution along rivers using the same method as for the affected flows based on the same rainfall data should be improved or changed completely.

Figure 7. Downstream balance condition, September 2012, Bystrica River

4. Conclusions
For the optimal and successful development, planning and predictions in water management, a detailed picture and knowledge of the need for water in space and over time is needed. Water management balances are one of the primary activities of water management in securing claims for water. This paper
describes the first attempt to apply an integrated water resource assessment and water availability model in Slovakia using WEAP software. We employed the relatively simple model structure afforded by this software to process the quantitative water management balance and to analyze the impact of individual elements that affect the Hron River for the period 2010 - 2015.

All the possible incompatibilities between the predefined model patterns and the predetermined methodological features in water allocation modeling, their applicability in existing assumption, Schemes. However, thanks to scripting and by the ability to create user-defined variables and assumptions. Expression Builder offers plenty of functions and the ability to refer to any variable from the data tree. The scheme management could be called poor at present compared to other GIS-based software with schemes. However, thanks to scripting, most of the scheme can be automatically created and also sorted by tags, which can be linked to user-defined filters. WEAP also includes tools not used in the case study that are worth mentioning. In the future, however, it will be necessary to verify their applicability in Slovakia, including the ability to link WEAP with MODFLOW [12] and MODPATH, which can be used to model groundwater in detail. There are internal variables and objects intended for modelling water quality and an additional option to link WEAP to software QUAL2K [13].

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