WATER BALANCE (WatBal) MODEL AND TUNING PARAMETERS

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Abstract: Water Balance model was developed by a group of authors closely bounded with the Water Area Research in the International Institute of Applied System Analysis. Model was recommended by the US EPA for the first co-ordinated judgment of possible climate change impact on water related problems in selected post socialist European countries. This model in its simplified version was chosen as the recommended model for the "Basin-Wide Water Balance in the Danube River Basin" Project which is performed within the IHP UNESCO co-operation on the field of Hydrology in this region. Set of quasiphysical tuning parameters play serious role in tuning the model. The aim of proper setting of parameters is minimisation of total balance error with respect to the initial and final water storage in different separately evaluated "layers" as follows: snow water content (surface storage), soil moisture in the upper soil layer (assumed to be 1 m deep), soil moisture content variation in deep soil (basin) horizons. Balance region is defined as a (sub) basin with the area of 5 000 – 10 000 km² related to the discharge gauging station. Computation is made for a virtual point located in the mean weighted elevation of studied basin (elevation median, basin elevation gravity point). Results of this water balance evaluation are consecutively used for spatial distribution of balance elements performing and tuning by the Institute of Hydrology of the Slovak Academy of Sciences.

Keywords: Danube basin, water balance, mathematical modelling, precipitation, areal evapotranspiration, runoff depth, digital terrain model, water divides, International Commission for the Protection of the Danube River (ICPDR).

DAS WASSERBILANZMODEL (WatBal) UND STIMMPARAMETERN

Zusammenfassung: Das Wasserbilanzmodell (WatBal) wurde von einer Gruppe von Autoren, die eng mit den Wasserproblemen im Internationalen Institut für angewandte Systemanalyse verbündet waren, zusammengestellt. Das Modell war für die erste koordinierte Schätzung der Klimaänderungenwirkung an mit Wasserverbundene Probleme, auf Grund der Empfehlung von US EPA, in bestimmten ehemaligen sozialistischen Staaten der Europa, benutzt. Die vereinfachte Version dieses Modells würde für Benützung im Projekt „Wasserbilanz im ganzen Donaueinzugsgebiet", in Rahmen der IHP UNESCO Zusammenarbeit in Hydrologie in diesem Gebiet, als ausgewählt empfohlen. Ein Satz von quasi-physikalisch Parametern spielt eine wichtige Aufgabe in der Modelleinstimmen. Ziel in richtiger Einstellung von Parametern ist die Erreichung von minimaler Fehler in totalen Wasserbilanzschätzung mit Berücksichtigung an Anfangs- und Endwerte von Wasservorrat in verschiedenen „Schichten", wie Schneedecke (Wasservorrat an der Oberfläche), Bodenfeuchte im Bodenschicht (oberen 1 m Schicht ist angenommen) und die Wasservorratsänderungen in tieferen Bodenschichten. Einzelne Bilanzgebiete sind als natürliche (Teil-) Einzugsgebiete mit der Flächengröße von 5000 bis 10 000 km² zum Abflußmeßstation definiert. Bewertung ist gemacht wie für einen virtuellen Punkt, der in der (gewägte) mittlere Einzugsgebietshöhe (Einzugsgebietshöhenschwerpunkt) lokalisiert ist. Diese Bewertungsresultaten sind weiter von der Institute für Hydrologie der Slowakische Akademie der Wissenschaften für die Gebietsverteilung von Wasserbilanzelementen und ihre Gebietssummenverifikation benützt.
Schlüsselworte: Einzugsgebiet der Donau, Wasserbilanz, mathematische Modellierung, Niederschläge, Gebietsverdunstung, Abflußhöhe, numerisches Terrainmodell, Wasserscheidelinien, Internationale Kommission zum Schutz der Donau (IKSD).

1. Introduction

WatBal model was developed on the base of the water balance equation. In principle the full version of the water balance equation includes not only input and output variables (precipitation, runoff depth and evapotranspiration) and parameters (full field soil moisture capacity, vertical extend of the basin, mean weighted elevation of the basin, etc.), but also some state variables, catchment storage incorporating water storage at the soil surface (generally the snow pack water equivalent), soil moisture content which significantly influences actual "areal" evapotranspiration and amount of water which is below the root zone and below the active soil layer influencing evapotranspiration at least by capillary rise. This portion of water (more exactly expressed: "the variations" of this portion of water – the total volume is not known) we will call the "deep water storage" and contribution to this storage is result of seepage when the soil moisture is greater than the soil full field moisture capacity.

It is possible to find in the world literature large amount of water balance equation analyses. Intentding to use mathematical model for water balance, which was introduced after the International Climate Change Programme started, we turned our attention to the model WatBal which was developed in the International Institute of Applied System Analysis - IIASA (Kaczmarek, 1993; Yates, 1994) and recommended by the US EPA for national climate change studies in some post socialist countries, where significant contribution and assistance was performed in the frame of the PHARE programme.

2. Description of the model

The water balance equation that connects precipitation, evapotranspiration, runoff, and catchment storage was first formulated by Penck (1896) and since then applied in many hydrological studies.

2.1. Background.

Theoretical approach and a programme for by us selected method of water balance assessment in a basin was formulated (DOS-version) by Kaczmarek (1993). In his conceptual model the input data are averaged for the river catchment and lumped parameters are used in the tuning / calibration process. This model includes also a rainfall (effective precipitation) – runoff model. Kaczmarek stresses a fact that storage parameters cannot be routinely measured, which highly complicates efforts to model the water budget equation.

It is supposed that all input and output variables are taken as uniformly distributed throughout the river catchment or a grid cells under consideration.

Correctness of conceptual representation of watershed processes may be only judged on the basis of differences between model results and some measurable hydrologic data e.g. runoff, it means that the tuning process can be based on the minimisation of differences between the observed runoff depth and the modelled one.

Kaczmarek in the runoff model component recognises three parts of runoff – immediate (surface), delayed and a base flow.

Potential evapotranspiration is a non-measurable variable and has to be calculated on the basis of other routinely measured climatic elements, such as radiation, air temperature, air humidity and wind speed. In the Kaczmarek paper is the reference to authors Brutsaert (1982) and Zubenok (1978).

Values of precipitation are usually obtained from recorded rainfall data adjusted in the winter season to changes due to snow accumulation and snow melting processes.

The model depends on 3 parameters to be determined by calibration, based on minimization of the mean square error of catchment outflows.

Kaczmarek recommends to investigate relationship between the model parameters and certain physical characteristics of river catchments.

2.2. WatBal by Yates

Model WatBal (Yates, 1994) is an attempt to use simple yet widely accepted assumption regarding the water balance and sound physical approaches for estimating potential evapotranspiration.

Model takes effective precipitation, potential evapotranspiration as input and "historic discharge" for calibration. Model produces the runoff response of a river basin as well as changes in other variables such as storage and evapotranspiration. Model is envisaged to be used as an integrated tool for modelling the response of river basin to potential climate change by applying "new" precipitation and "new" potential evapotranspiration in the calibrated model without further tuning parameters change ("new" estimated variables used in chosen potential evapotranspiration calculation method) which are expected due to the climate change impact.

For larger basins with long times to concentration, longer time steps are recommended. For the computation of **effective precipitation** in regions where snowmelt makes up a substantial portion of the runoff water, a temperature index model was used with the upper and lower temperature bounds defined by trial and error. This means that in the model exists a "hidden" component representing a water content of the snow pack layer.

Priestly – Taylor radiation method was selected for the calculation of **potential evapotranspiration**. This method requires the data on radiation balance of the studied surface as input values (knowledge of land cover and snow period is assumed for estimating albedo range).

WatBal counts with changes in the **soil moisture** precipitation, runoff, actual evapotranspiration, while using potential evapotranspiration to drive the extraction of water from the soil moisture (Figure 1).

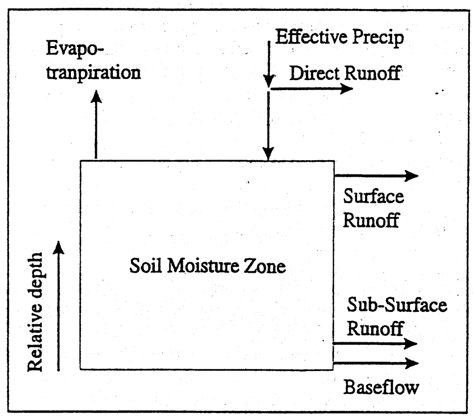

Figure 1. Conceptualization of the water balance for the WatBal model.

As can be seen from the Figure 1, **runoff** has 4 terms, for which some tuning parameters need to be introduced.

For basins with a large portion of runoff from **snowmelt**, a temperature index mf_i for snowmelt model is used with temperature thresholds for melting T_l and freezing T_s, creating an "adjusted" effective precipitation $Peff_i$. in time step i

$$Peff_i = mf_i \,(A_{i-1} + Pm_i) \qquad (1)$$

where A_i = snow accumulation in time step i

Pm_i = "observed" precipitation in time step i

and

$$mf_i = \begin{cases} 0 & for \quad T_i \le T_s \\ 1 & for \quad T_l \le T_i \\ (T_i - T_s)/(T_l - T_s) & for \quad T_s \le T_i \le T_l \end{cases} \tag{2}$$

and snow accumulation A_i in time step *i* is written as

$$A_i = (1 - mf_i)(A_{i-1} + Pm_i) \tag{3}$$

Model is written in Visual Basic Programming language within Excel-5.0, but program was obtained in the form of an Excel file with hidden programming part. According to Yates (1994) the direct runoff coefficient and parameter for sub-surface factor are not part of the optimization routine.

In the Water Research Institute (WRI) Bratislava this model was verified in our climate change impact study for the Nitra River basin (Petrovič, 1998a, 1998b). By running the model it was found that for certain combinations of T_s and T_l model is not tuneable (convergence of parameters solution was not stable). This gave us an impulse to rewrite the model according to known formulated equations for particular components of water balance with certain modification of snowmelt, total runoff and evapotranspiration estimation conception.

2.3. Modification of WatBal by WRI Bratislava

The WatBal model conception was taken as a base for our further study. The assumption that basin can be substituted by the virtual point in lumped approach to modelling was kept. A general approach to our solution was described by Petrovič (2002). Due to this, here in the paper only main steps of model application and all important changes since 2002 are described.

The virtual point representing the studied basin is located in the "reference" elevation a.s.l., which is the weighted elevation average, h_w in the basin:

$$h_w = (1/A).\int_{h\,min}^{h\,max} A(h).dh \tag{4}$$

Function *A(h)* represents distribution of area in the basin with the elevation from *h* to *h+dh*. In usual situation this function is not linear and very often it is difficult to find an analytical function representing such vertical distribution of the area in the real basin. This also means, that this elevation weighted average h_w does not represent the median of elevations in the basin, for which 50% of area is below and 50% of the area is above this median. When speaking about the minimal h_n elevation in the basin (elevation a.s.l. of the closing profile) and the highest elevation on the water dividing line h_x then our h_w is not a middle of the interval $<h_n;h_x>$. All values of elevation, which will be used in further computation, can be estimated from the digital terrain model of the studied basin.

From above given explanation it follows that a balance region is taken as a "virtual point" located in the reference elevation of the basin. As precipitation input the areal mean of precipitation is taken, it means precipitation estimated from GIS approach or from the linear increase of precipitation with elevation computed for the reference elevation value. The runoff depth is taken as volume of discharge in the closing profile divided by the total basin area and duration of time step. Actual evapotranspiration is computed within the model run in monthly time step.

Model was re-written in components for separate estimating of areal precipitation based on as many as possible stations in the basin (and nearest surroundings), separate estimation of potential evapotranspiration on the base of air temperature and air humidity using the Budyko – Zubenok – Konstantinov (1971) method.

Assessment of precipitation, air temperature, logarithm of air humidity (expresssed in vapour pressure) for the reference elevation in the studied basin was not changed, the linear vertical gradient was used and calculation was performed for each month of 30 years period separately in EXCEL using function TREND and keeping parameters in TREND function giving non-zero “b” coefficient of linear regression.

Potential evapotranspiration, in principle, is in our modification estimated according to Budyko and Zubenokova (Kuz’min, 1976; Konstantinov, 1971). Set of nomograms was digitised and incorporated into the program in Fortran77. Value of potential evapotranspiration PET is obtained in columns representing given month as an interpolation between lines giving values for computed saturation deficit. In our case the nomograms for a range of geo-botanical regions called in Russian literature as forest, forest-step and step can be selected and used. Example of nodes for forest-step is given in the Table 1. Last year also this program was re-written into EXCEL and data shown in Table 1 create look-up table in EXCEL.

Table 1. Mean monthly potential evapotranspiration in mm per day for forest-step as a function of months and saturated deficit in hPa (milibars).

SatDef	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
0	0,084	0,097	0,161	0,250	0,565	1,330	0,968	0,387	0,233	0,129	0,100	0,084
1	0,403	0,548	0,742	1,170	1,710	2,430	2,130	1,390	0,933	0,645	0,567	0,403
2	0,710	0,919	1,290	1,820	2,360	2,900	2,630	2,070	1,550	1,270	0,950	0,710
3	0,968	1,270	1,730	2,270	2,770	3,270	3,000	2,500	2,020	1,520	1,280	0,968
4	1,100	1,580	2,090	2,650	3,070	3,590	3,230	2,840	2,400	1,840	1,630	1,100
5	1,440	1,860	2,400	3,000	3,370	3,880	3,610	3,140	2,750	2,160	1,920	1,440
6	1,470	2,080	2,680	3,270	3,610	4,130	3,860	3,400	3,060	2,400	2,150	1,470
7	1,480	2,290	2,960	3,570	3,860	4,370	4,100	3,640	3,330	2,680	2,370	1,480
8	1,490	2,500	3,250	3,800	4,080	4,600	4,310	3,870	3,580	2,950	2,570	1,490
9	1,500	2,510	3,260	4,030	4,290	4,820	4,520	4,100	3,820	2,960	2,580	1,500
10	1,510	2,520	3,270	4,230	4,470	5,000	4,710	4,290	4,020	2,970	2,590	1,510
11	1,520	2,530	3,280	4,400	4,660	5,180	4,890	4,450	4,230	2,980	2,600	1,520
12	1,530	2,540	3,290	4,410	4,820	5,350	5,050	4,630	4,440	2,990	2,610	1,530
13	1,540	2,550	3,300	4,420	4,980	5,520	5,230	4,810	4,450	3,000	2,620	1,540
14	1,550	2,560	3,310	4,430	5,150	5,680	5,370	4,950	4,460	3,010	2,630	1,550
15	1,560	2,570	3,320	4,440	5,290	5,830	5,500	5,100	4,470	3,020	2,640	1,560
16	1,570	2,580	3,330	4,450	5,440	5,950	5,630	5,240	4,480	3,030	2,650	1,570
17	1,580	2,590	3,340	4,460	5,580	6,080	5,760	5,390	4,490	3,040	2,660	1,580
18	1,590	2,600	3,350	4,470	5,710	6,200	5,890	5,520	4,500	3,050	2,670	1,590

Full set of necessary details and programs for complex application of WatBal was explained and distributed among experts for water balance nominated by participating countries at the XXIst Conference of Danube countries in Bucharest. By detailed study of this set of programs (till now only) 2 problems were found in equation formulation for evaluation of liquid precipitation and snow cover water equivalent and thanks to Mr. H. Kling (AT) and Mr. S. Lejska (CZ) particular cells were corrected.

Initially parameters in the model were tuned after introducing the rainfall - runoff model using the method trial – error. Such approach is needed if the model is to be used for climate change impact study because the tuned model on „historical” runoff data is assumed to be consistent in time when modelled input with changed data for precipitation, air temperature and air humidity (potential evapotranspiration) is applied. But the condition for „historical data” application in the calibration process is assumption that selected „historical period” was not visibly influenced by global and / or climate change.

It is known (Lapin, 1999), that latest „almost not influenced” representative period in sense of the WMO definition is the period of 1951 – 1980. Practical reasons (difficult availability of digitized meteorological data for the period 1951 – 1960 but also difficulties in finalising data for decade 1991 – 2000 in time) led the Project Steering Committee to select the period of 1961 – 1990 for general model use, optionally 1951 – 2000, as when the whole basin assessment should be homogenised as much as possible the only above mentioned 30 years are used.

After such a decision difficulties were found in quasi-stability of deep water storage below the top soil layer and something like drying was resulting from the model. Figure 2 shows monthly values of deep soil water storage obtained (c6) by the initial version of the model which included the rainfall-runoff routine and was tuned for the period of 1951 – 1980. Application of obtained parameters without change on the input data for the period 1961 – 1990 results in curve (c7). Decrease of the deep water storage in latest 10 years is here visible. To tell the truth, the general decrease of springs capacity is also occurred in practice but we should tune the model with assumption that used calibration period is accepted as suitable.

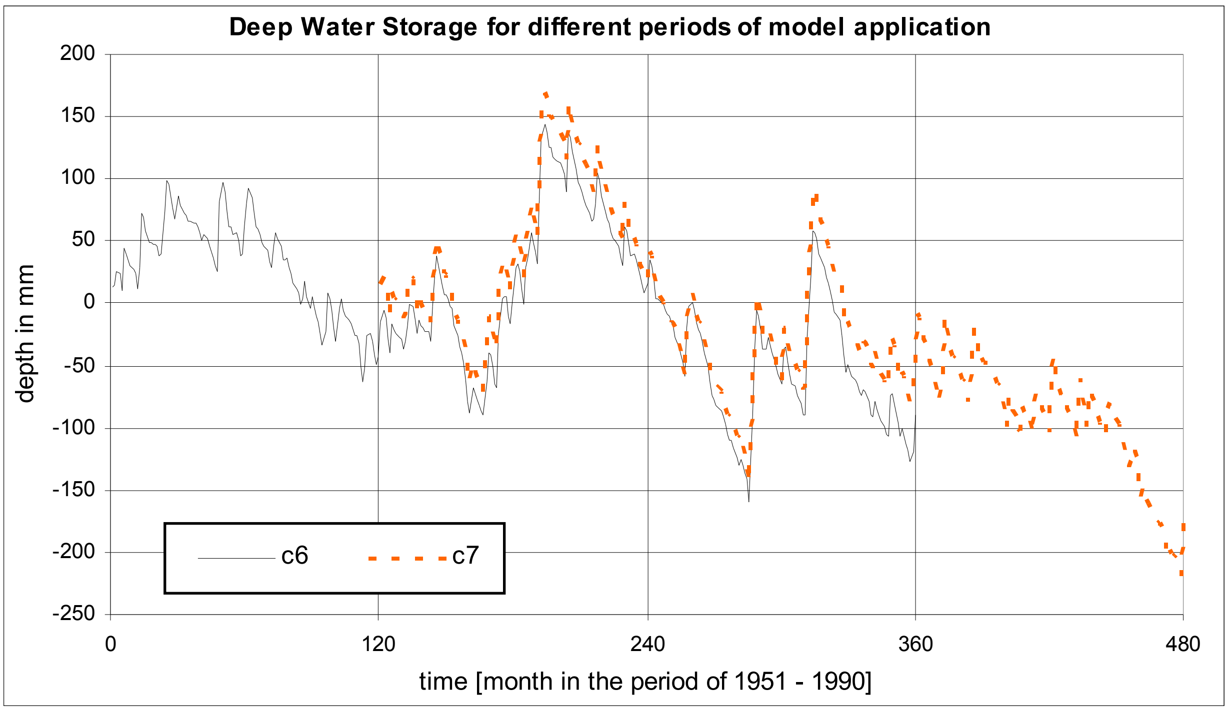

Figure 2. Deep soil water storage for the periods 1951 – 1980 and 1961 – 1990 by computing both periods with parameters derived for the period 1951 – 1980 incl. runoff modelling.

Obtained results approve that also tuning / calibration of the model depends on the representative period selection. In principle, in modelling activity the definition of the representative period by the WMO can be discussed. Why does the period have duration (e.g.) of 30 years? Sun spot cycle has 11 years, etc.

This phenomena - giving the risk that parameters by use of the runoff component will not be set up properly - caused decision on the tuning of the model on the minimised final balance error and optimised long term mean (set it as close as possible to zero) of the deep water storage.

Similar situation for the model tuned without a runoff component – in the version in which it is used for the project Basin-Wide Water Balance in the Danube Basin is shown in Fig. 3.

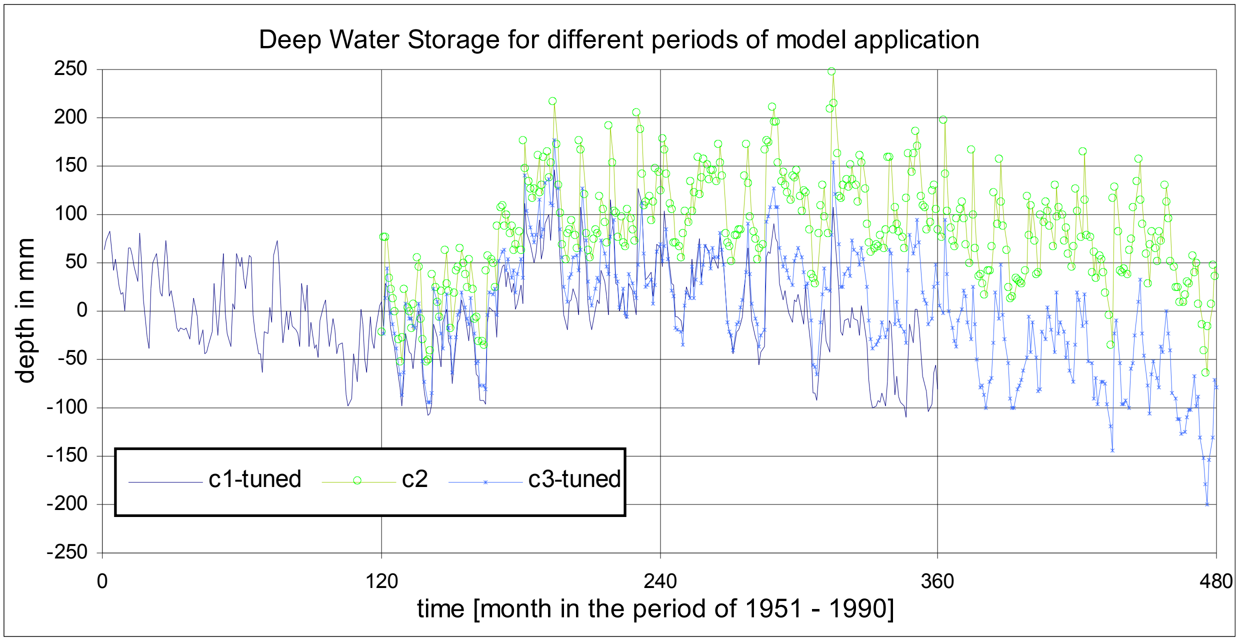

Figure 3. Deep soil moisture storage for the periods 1951 – 1980 and 1961 – 1990 computed for c1 and c2 with parameters derived for the period 1951 – 1980, curve c3 is tuned for the period of 1961 – 1990.

Application of parameters derived for the curve 1 in the period 1951 – 1980 is probably not favourable in the period 1961 – 1990, where the curve c3 with revised calibration for the second period is again reflecting decrease of deep water storage in the basin.

3. Tuning parameters used in the model

Since the XXI[st] Conference in Bucharest, where the model was introduced (Petrovič, 2002), we made some modification in parameters meaning and setting. Experts in the Danube basin, which were nominated to participate in the Water Balance Project by their NC IHP UNESCO, are familiar with the present situation. Let us recapitulate the present situation.

Reference "zero" elevation is the value h_w obtained on the base of the equation (4) using GIS or other way of estimation.

The lowest point in the basin h_n and the highest point h_x estimate a frame for the temperature limits ATSNOW and ATRAIN.

The assumption is that for the temperature in the lowest point of the basin equal to zero or less than zero, the negative temperature is in the whole basin and all the precipitation is in a solid form (snow). On the other hand, if the temperature in the highest point of the basin is equal to or higher than zero, we can assume that all the precipitation in the basin is in a liquid form (rain). For the first estimation of ATSNOW and ATRAIN values the vertical adiabatical temperature gradient -0.0065 °C / m can be used, it means:

$$ATSNOW = -0.0065(h_w - h_n) \qquad (5)$$

$$ATRAIN = -0.0065(h_w - h_x) \qquad (6)$$

and a help variable is

$$ATMIX = ATRAIN - ATSNOW \tag{7}$$

Based on above formulated thresholds the initial values of ATSNOW and ATMIX are for disposal. According to the equation (2) for temperature T inside the temperature interval with mixed precipitation the temperature index mf_i can be written in a form

$$mf_i = (T - ATSNOW) / (ATRAIN - ATSNOW) = (T - ATSNOW) / ATMIX \tag{8}$$

Here it is necessary to mention that reference level is not in the arithmetical elevation mean, so the value mf_i does not represent percentage of the basin area with the temperature below zero. On the other hand, the tuned values ATSNOW and ATRAIN as a result of calibration can differ from values obtained from equation (5) and (6) and could better express phenomena bounded with the nonlinear distribution of area with the elevation.

Furthermore, couple of parameters create full field capacity (WSFFC) and critical soil moisture (WCRIT). The first one plays role at estimating seepage below the top soil layer. If actual soil moisture (WACT) is above the value of WSFFC, all the surplus water infiltrates into deeper layer and increases the model variable value (in the model assigned as WDELTA). The second one (WCRIT) is usually assumed to be equal to WSFFC and represents linear factor for actual evapotranspiration from estimation of potential one – see eq. (9). All the soil moisture values in the model are expressed in term of available water depth, so they are values above the wilting point.

$$AET = PET * WACT / WCRIT \tag{9}$$

In the process of calibration at the beginning it is assumed *WSFFC = WCRIT* and by using the expression

$$WCRIT = WSFFC * (0.5 + (ABS(x)/(1 + ABS(x))) \tag{10}$$

fine tuning in EXCEL can be performed by optimising parameter x. Resulting WCRIT from the eq. (10) will differ from the WSFFC by less than 50 %.

Next sophisticated parameter represents “melting capacity” by given air temperature (related to the reference elevation). In short time step modelling and in flat areas so called “degree factor” can be introduced. In models working in daily time step that value, according to the author’s personal experience, is very close to value 4 [mm / 1 °C]. A simple multiplying of this value by the amount of days in the time step could be done only on the assumption, that there is enough snow in the whole vertical extent of the basin. At calibration we could start with the monthly value MDGFAC around 120 but at the tuning process this value should not grow. The acting temperature at snowmelt is (T – ATSNOW) and by considering the temperature index – eq. (8) – the melting capacity can be for ATRAIN > **T** > ATSNOW written in a form:

$$SNOWMELT = MGDFAC * (T - ATSNOW)^2 / ATMIX \tag{11}$$

In this equation all the parameters on the right side are tuneable for given basin. Value of SNOWMELT represents melting capacity and if the accumulated water in the snow pack in the basin is lower, then all the snow pack will melt in given time step.

Latest used parameter in our modification of WatBAl is „PRIESKO" which represents a "fast infiltration coefficient" and gives a portion of liquid (monthly) precipitation which enters formally (is taken as infiltrated into) the soil layer at the beginning of a time step and plays role in the AET evaluation; it must be from the interval <0; 1>, the resting part (1-PRIESKO) of liquid precipitation is used at the end of the time step in the soil moisture increase before starting the next time step.

4. Discussion and conclusions.

In the initial version of WatBal by Yates it was mentioned that all four runoff components were not included in the calibration process and it was recommended to develop the runoff routine outside the WatBal application.

This was the reason why we simplified runoff procedure to one equation only, giving the total runoff as the value obtained from two-dimensional linear equation, and as variables were taken values of liquid portion of precipitation and soil moisture content in given time step. Formally runoff was subtracted from the deep water storage. This internal variable in fact represents variation of the total deep water depth of the basin, sometimes called as the basin water holding capacity, which estimates the base flow component. Estimation of this absolute storage is non realistic. Tuning of the model was performed by trying to minimise the sum of square errors and simultaneously to set the total balance error as close as possible to zero. Also the snow pack is in the model computed as an internal variable (WSURF) which represents the upper limit for computed snowmelt in given time step. It means that we have slightly modified conceptualization of the water balance.

The next simplification was made (as mentioned above) due to the doubt about the representativeness of the selected period for model run both because the climate change impact in given period seems to be visible and representativeness of the length of the data set having just 30 years is disputable. It means we left out the runoff routine and the tuning process is based on the setting of the total balance error and mean value of deep water storage as close as possible to zero. Here it was found that it is difficult to get „hard zero" for both characteristics when assuming the same initial and final values (in the „zero-th" time step and the 360th time step) for soil moisture WSMC and surface water storage WSURF. The autumn in the year just before the beginning of the processing period can be different from the autumn in the latest year of model run. In practical application of calibration process greater weight should be given to set up at least the mean of deep water storage as close as possible to zero and the error in absolute water balance equation in the range of units seems to be acceptable.

Theoretically, it would be very useful in very precise studies for impact analysis or for detailed study of yearly course of modelled evapotranspiration and/or runoff to have at least one year as the "warming-up cycle" before the error minimisation starts. From that follows a difficult idea to use only period starting with the second year for calibration and trends analysis in the 30-year period. Than the input state variables are values modelled for the end of the "warming-up cycle" it means values e.g. in December of the first year.

For the purpose of this study to prepare the basin-wide water balance the applied approach gives results which improve existing basin-wide water balance published in the first Danube monograph (Stančík, Jovanovič, 1988).

Application of simplified model WatBal without considering runoff component, due to the accepted method gives more than satisfactorily results for selected balance regions and Project intentions on the mean yearly base.

Ackowledgments

This study was performed within the participation of Slovakia and namely the Water Research Institute in the IHP UNESCO Project

"Basin – wide water balance in the Danube River basin".

Model should be used for balance estimation in selected (sub) basins with the drainage area between 5000 – 10000 km^2 in all Danube countries. Methods were analysed and approved by 4 experts meetings and 3 Steering Committee Meetings. Processing should be now in its final stage.

The International portion of work related to the co-ordination of the Project and to the cost of Steering Committee and expert meetings is supported by the UNESCO Regional Bureau for Science in Europe (ROSTE) under the contract No. 875.804.3.

International coordination is managed by Slovakia and local duties related to the work of the co-ordination team are financially supported by Science and Technology Assistance Agency under the contract No. APVT-99-18202

The full version of the model can be obtained per E-mail on request.

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