CHANGES OF FLOODS TRAVEL TIMES ON UPPER DANUBE

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Abstract: In the first part of the paper the analysis of the travel times for historical floods before Danube channel changes and for floods during last 20 years was made. Travel times of extreme floods are of particular importance for hydrological forecasts and flood warnings. The dependency of the flood travel times on peak water level in the upper station is studied in the second part of the paper for the period 1991–2002. The analysis of three river reaches (Achleiten–Bratislava, Ybbs–Bratislava and Kienstock–Bratislava) is based on 83 flood waves (hourly or 3-hrs water levels), which exceeded the 250 cm water level in Bratislava. The results show that the travel times of 1991–2002 are shorter by about 41% compared to 1923–1966 and by about 11% compared to 1975–1991 what may be caused by Danube channel training. In the third part of the paper both, non-storage routing calibration method for forecast of water levels at Bratislava station and nonlinear cascade routing model for forecast of discharge at six stations between Kienstock and Nagymaros were developed.
Keywords: Danube river, travel time changes, non-storage routing method, nonlinear cascade routing model, forecasting

VERÄNDERUNG DER LAUFZEITEN DER HOCHWÄSSER DER OBEREN DONAU

Zusammenfassung: In den ersten Teil des Aufsatzes ist die Analyse der Laufzeiten der historischen Hochwassewellen dargestellt, die bevor der Donauflussbettänderungen vorkamen, sowie auch der Wellen der letzten 20 Jahren. Die Laufzeiten der extremen Hochwasserwellen sind besonders wichtig fűr hydrologische Vorhersagen und Warnungen. In den zweiten Teil des Aufsatzes ist die aus der Periode 1991–2000 bestimmte Abhängigkeit der Hochwasserlaufzeit von den Höchstwasserstand in den oberen Donaupegel der betreffenden Flussstrecke analysiert. Diese Analyse war fűr drei Flussabschnitte durchgefűhrt, und zwar fűr Achleiten - Bratislava, Ybbs - Bratislava, und Kienstock - Bratislava. Sie beruht auf 83 Hochwasserwellendaten (mit Zeitschritt 3 Stunden) die den Wasserstand 250 cm auf dem Pegel Bratislava űberschritten. Die Ergebnisse zeigen, dass die Laufzeiten der Zeitspanne 1991–2000 um etwa 41% kűrzer sind verglichen mit denen der 1923–1966 Periode, und um 11% kűrzer als die der 1975–1991 Zeitspanne. Dies ist wahrscheinlich auf die Donau Flussbettregulierung zurűckzufűhren. In den dritten Teil des Aufsatzes ist die Entwicklung von zwei Modellen fűr Fortpflanzung der Donauhochwasserwellen dargestellt. Die erste Methode beruht auf der Regression der Wasserstände zwischen verschiedenen Donaupegeln und bezűglichen Laufzeiten, das zweite Modell auf der Simulierung der Hochwasserwellenbewegung durch eine hypothetische nichtlineare Speicherkaskade. Die erste Methode ist auf der simulierten Wasserstandsvorhersage fűr Bratislava Pegel demonstriert, die zweite dann auf solcher Durchflussvorhersage fűr sechs Pegel zwischen Kienstock und Nagymaros.
Schlüsselwörte: Donaufluss, Flusswellenlaufzeitänderungen, Nichtlineare Fortpflanzung von Hochwässern, Hochwasservorhersagen

Introduction

Important changes of transport and transformation capacities of the Danube river channel occurred, mainly at low and middle stages, due to anthropogenic activities in last century. Channel training resulted in shortening of the floodwave travel times. This fact was indicated by several authors, e.g. Cizova (1992), Hajtasova et al. (1995), Zsuffa (1999), Svoboda et al. (2000). Cizova (1992) as well as Hajtasova et al. (1995) indicated that the travel times (mainly of smaller flood waves) on the upper part of Danube decreased by 25-30 per cent. Zsuffa (1999) analyses the daily water stages before and after 1976 concluding the increase of small and middle floods in last years. It may happen due to channel training of upper Danube, which changed the superposition of floods on main stream and tributaries. According to Svoboda et al. (2000) the analysis of daily discharges indicated that the daily discharges at Bratislava were smoother and the long-term mean discharge was lower in last decade of the 20th century compared to the reference period of 1930–1980. The 30-day discharge decreased by more than 300 m^3s^{-1}, 364-day discharge increased by 160 m^3s^{-1}.

The volume of transported suspended and bed load gradually decreased in the middle reach of Danube due to construction of the reservoirs on German and Austrian reach. The deepening of the channel below Devin (Slovakia) and the consecutive fall of the groundwater level resulted in unfavourable conditions (Figure 1). The gravel excavation below Bratislava was stopped after 1980. The new Danube dam near Cunovo increased the Danube water level at Bratislava after November 1992. Decrease of flow velocities and stream turbulence caused the sedimentation of bed load (originally transported by the stream into lower profiles) in Danube channel in Bratislava. According to Opatovska (2002) it caused the expected planned sedimentation and channel bottom rouse and increase of the water level in station Danube: Bratislava. Misik and Capekova (2001) estimated that the Q_{100} water level in Bratislava should be by 20 – 25 cm higher in 1998 compared to 1996 due to changes in channel geometry and backwater.

These changes will require modification of the forecasting methods for station Danube: Bratislava used in operational service. In this respect the Institute of Hydrology SAS in collaboration with the Slovak Hydrometeorological Institute develops one theme of the international trilateral project "Improvement of the flood forecasting in middle Danube basin". Targets of the paper are:

1. The analysis of the travel times for historical floods before Danube channel changes and for floods during last 10 years;
2. The development of relationships of the flood travel times on peak water level in the upper station;
3. The forecast of water levels in Bratislava station using simple non-storage routing model REMOD and forecast of discharge using river model of non-linear cascade NLN-Danube.

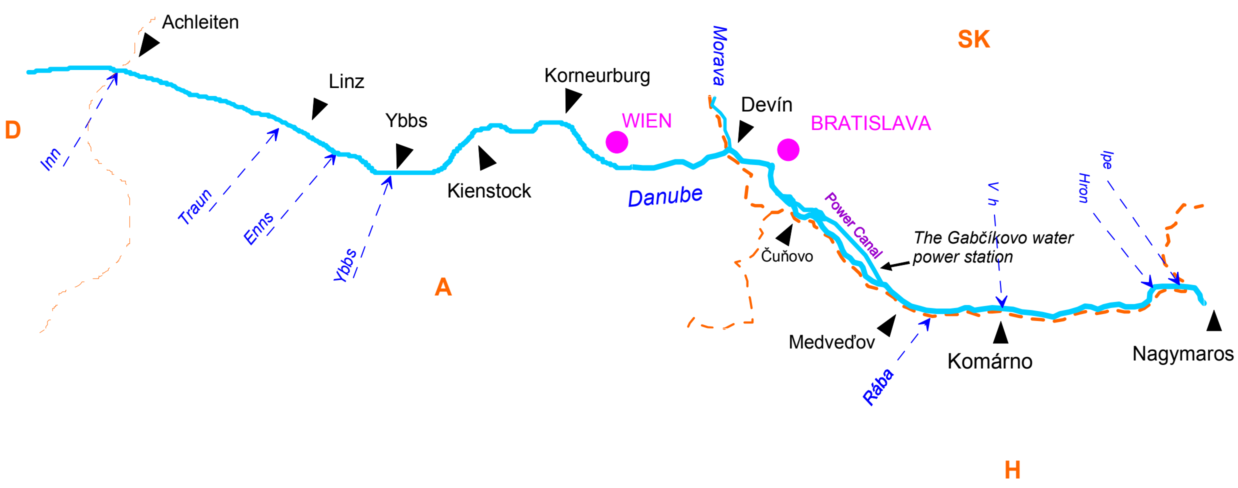


Figure 1. Scheme of the Austrian and Slovak part of Danube.

1 Analysis of the flood wave travel times changes in upper Danube

The upper part of the middle Danube river creates border of Slovakia between rkm 1708.2 (mouth of Ipel) and rkm 1880.2 (mouth of Morava) in the length of 172 km (Figure 1). About 7.5 km is the state border with Austria, 22.5 km is on Slovak territory and the rest of 142 km is the state border with Hungary. Between the Vienna basin and the Danube lowland the Danube river flows in concentrated channel with relatively high slope. After leaving the Small Carpathians it keeps the slope and flows on the own alluvial cone in complicated network of river branches downstream to Medvedov.

In the first part of the paper we analyse the travel times of the historical floods before the construction of the main reservoirs on the upper Danube (floods of 1954, 1965, 1975) and of the later floods (years 1981, 1985, 1991, 1997). In Figure 2 we can see that the travel times of the important floods in the reach Ybbs-Bratislava were between 55 and 80 hours in 1954–1965, while only 24–39 hours in 1991–2002. During the 1954 flood the travel time Ybbs – Bratislava was 78 hours (flow velocity v=0.69 m.s^{-1}) and in 1991 the travel time was only 39 hours (v=1,292 m.s^{-1}) in the same section.

Interesting is also the 2-peaks flood of July 1997, when both flood waves separated by modest decrease reached at almost the same water levels travel times of 26 hours (peak water level at Devin H_{KDE} =766 cm, v=1.93 m.s^{-1}) and 24 hours (H_{KDE} =760 cm, v=2,08 m.s^{-1}), respectively, between Ybbs – Bratislava (Bors, 1998).

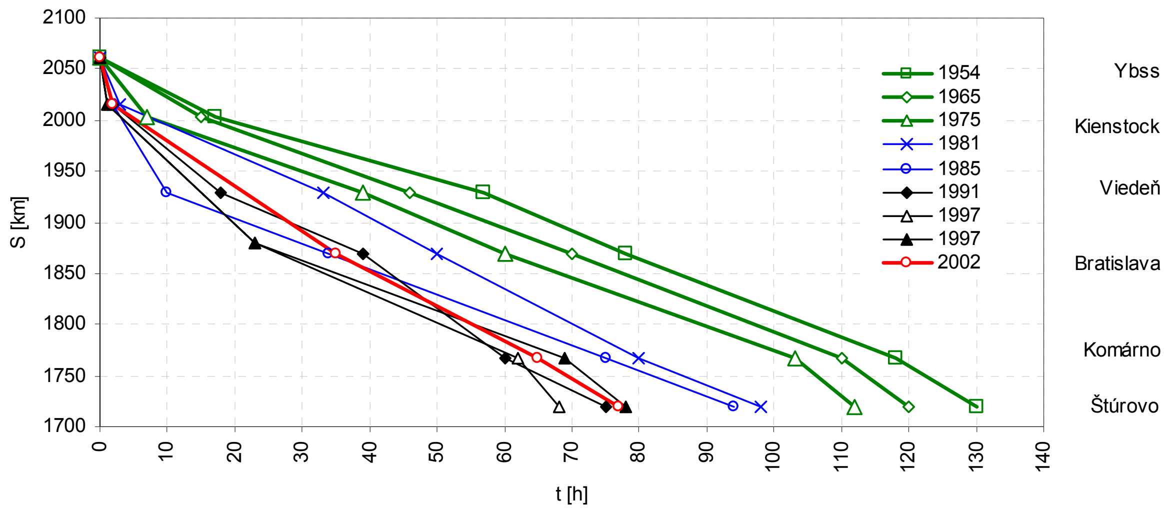


Figure 2 Travel times (t) of selected floods in 1954–2002, S - river km.

1.1 Derivation of the empirical relationships for estimation of peak level travel times for Bratislava

It is necessary to adapt the forecasting methods to the recent conditions in the basin taking into account the continuously changing conditions of flood waves propagation on Danube. At the same time it is necessary to find the mathematical expression of the graphical relations in order to develop mathematical models of the travel times.

The non-storage routing method was used for estimation of the travel times (Svoboda & Hajtasova, 1996; Kunsch et al., 1999; Martinka & Minarik, 1985; Laurenson & Mein, 1995; Mitkova, 2002). The travel times of the corresponding water levels can be estimated as:

$$\tau_i = t_{i,H_h} - t_{i,H_d} \tag{1}$$

where: $t_{i,Hh}$ – time of occurrence of the peak level at the upper station (subscript h);
$t_{i,Hd}$ – time of occurrence of the corresponding peak level at the lower station (subscript d).

We are searching the function:

$$\tau = f\,(H_{h,})$$ (2)

where: H_h – peak water level in upper station [cm];

τ – travel time [hours].

The basic data set for development of relations in 3 sections:

1. Achleiten – Bratislava,
2. Ybss – Bratislava, and
3. Kienstock – Bratislava

included 83 waves (hourly, or 3 – hour water levels) during which the peak level was over 250 cm in station Bratislava. Results of the analysis were drawn as graphs of relation and the relationships were developed between travel times for station Bratislava and peak water levels of floods in upper station in period 1991–1999 (Figure 3a,b). The quadratic relationship was used to express the relation between travel times and peak water levels in the upper station:

$$\tau = a + b.H_h + c.H_h^2$$ (3)

The relationships between travel time and peak water level in upper station are as follows:

1. Achleiten – Bratislava	$\tau = 85.86 - 0.326.H_h + 0.0004.H_h^2$	(3')
2. Ybbs – Bratislava	$\tau = 27.17 - 0.087.H_h + 0.000124.H_h^2$	(3'')
3. Kienstock – Bratislava	$\tau = 28.19 - 0.091.H_h + 0.0001018.H_h^2$	(3''')

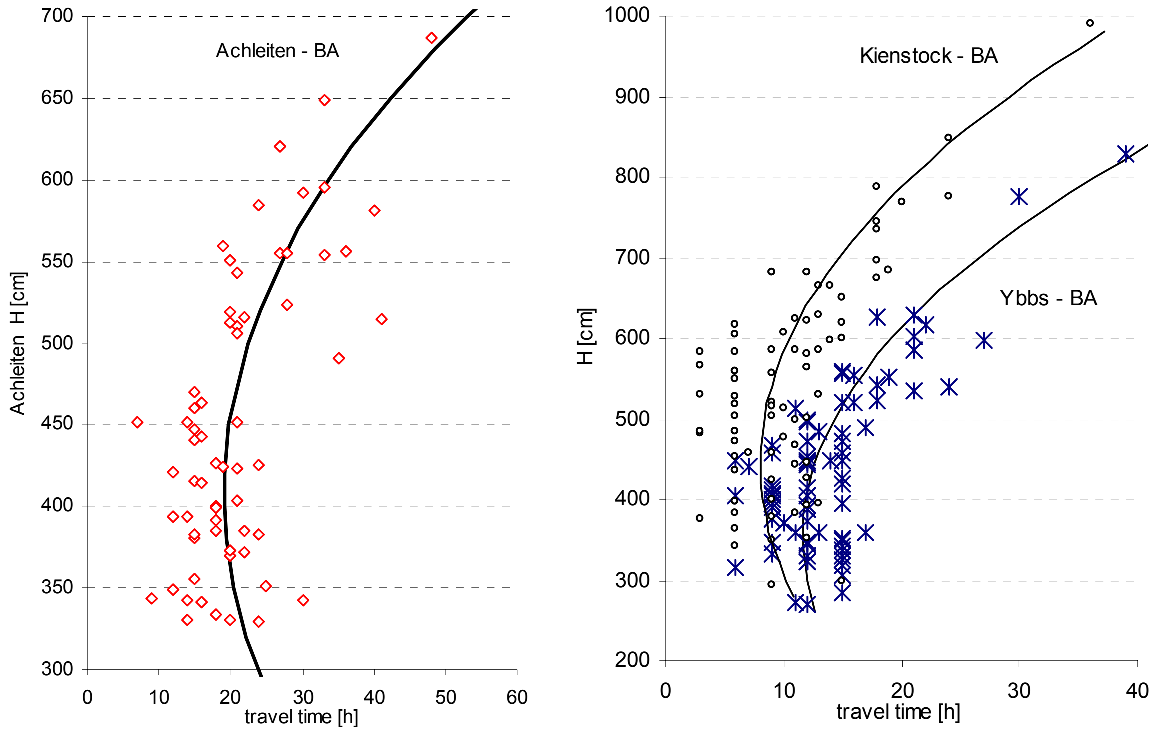


Figure 3 Travel times of the peak water level (1991–1999)
a) Achleiten – Bratislava,
b) Ybbs – Bratislava and Kienstock – Bratislava.

In Figure 3b we can see that for the peak water levels between 300 cm and 500 cm the travel time varies between 8 and 20 hours in Ybbs, the mean being about 14 hours. The difference of about 3 hours between travel times Ybbs – Bratislava and Kienstock – Bratislava is visible in the figure. The travel times of the period 1991–1999 were interpolated (based on flow velocity) to station Linz and compared with graphs of periods 1923–1966 and 1975–1991 for the section Linz–Bratislava presented by Cizova (1992) (Figure 4).

The analysis has shown that the mean travel time of the waves with peak levels between 300 cm and 500 cm was 29 hours in 1923–1966 (Linz – Bratislava). It means that the travel times of 1991–1999 (related to Linz) are shorter by about 41% compared to 1923–1966. In 1975–1991 the mean travel time of the section was 19 hours what represents the decrease of the mean travel time only by about 11%.

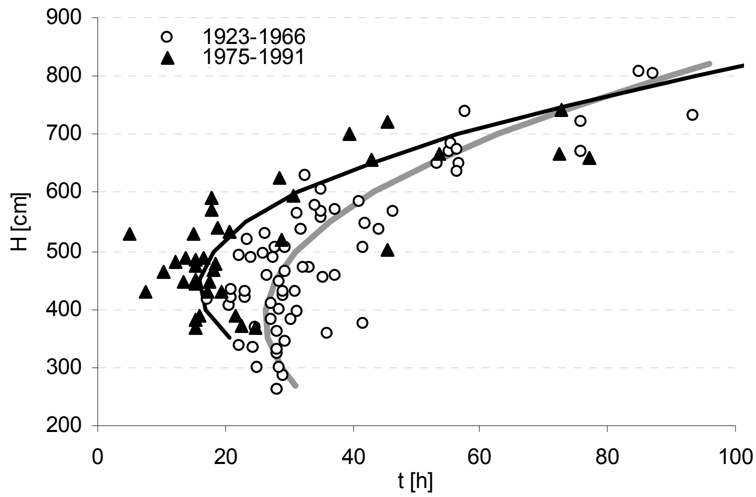


Figure 4 Travel times (t) of the peak water levels Linz – Bratislava according to Cizova (1992).

2 Update of the travel times forecasting relationships Kienstock – Bratislava in 1991–2002

Relationships for estimation of the travel times were analysed in more detail on flood of August 1991. The validity of the relationships was verified on data of flood in March 2002.

<u>August 2001 flood</u>

The biggest flood on the upper Danube since the catastrophic flood in 1965 occurred in August 1991 with the maximum water levels in Achleiten 687 cm (4.8. 0:00 hod), Ybbs 830 cm (8649 m^3s^{-1}, 4.8. 9:00), Kienstock 991cm (9722 m^3s^{-1}, 4.8. 12:00), and Bratislava 859 cm (9430 m^3s^{-1}, 6.8. 4:00). Rich 3-day precipitation and high saturation of the basin by previous smaller flood (Figure 5a) caused the flood. Due to the saturation the runoff response was very fast and high (HIPS, 1992). The travel times were estimated from the graphical record of the water levels in Kienstock and Bratislava. The 3-hour data of water levels were available in both stations.

Following equations were found for the travel time τ between Kienstock and Bratislava related to water level H_{Kl} in Kienstock for the 1991 flood:

Discharge increase:

$$\tau = 61,3645 - 0,249425 H_{Kl} + 0,00036 H_{Kl}^2 - 1,339.10^{-7} H_{Kl}^3 \qquad (4)$$

Discharge decrease:

$$\tau = - 50,1121 + 0,176425\, H_{Kl} - 9,13836.10^{-5} H_{Kl}^2 \qquad (5)$$

where: τ – travel time [hour];
H_{Kl} – water level in Kienstock [cm].

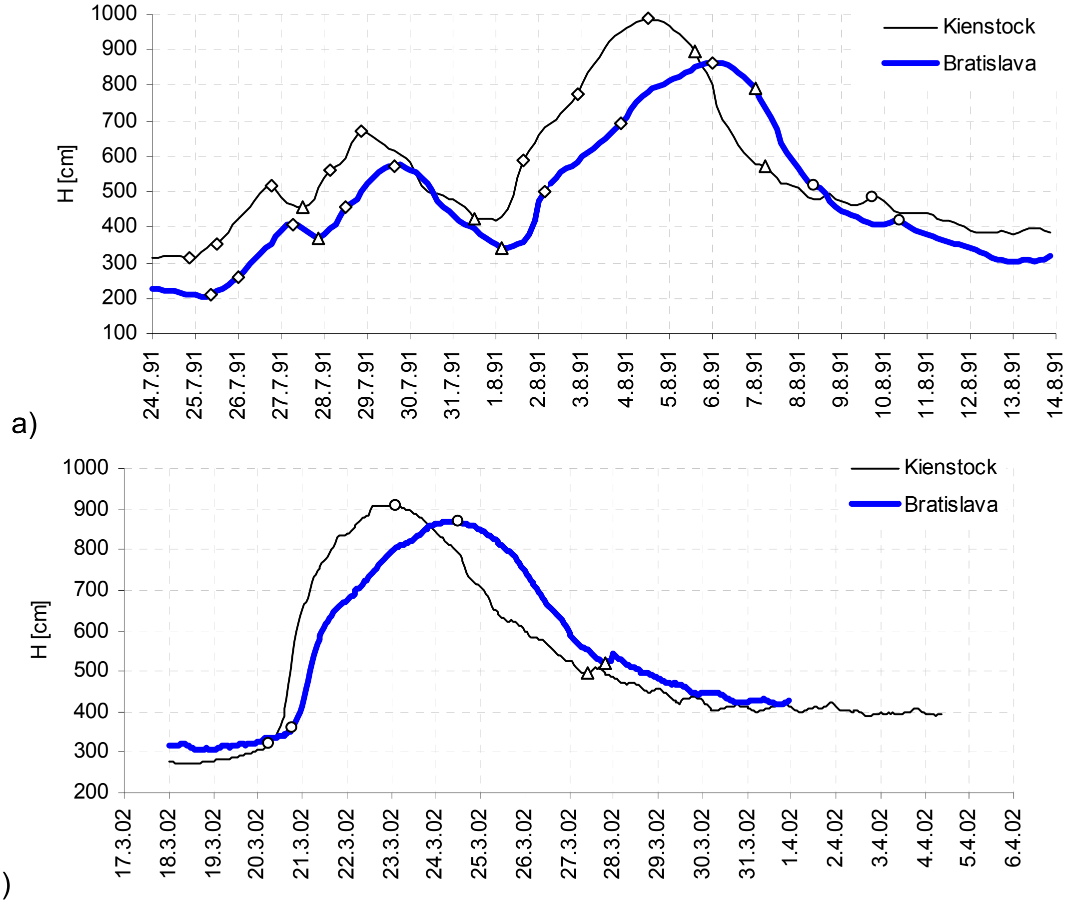


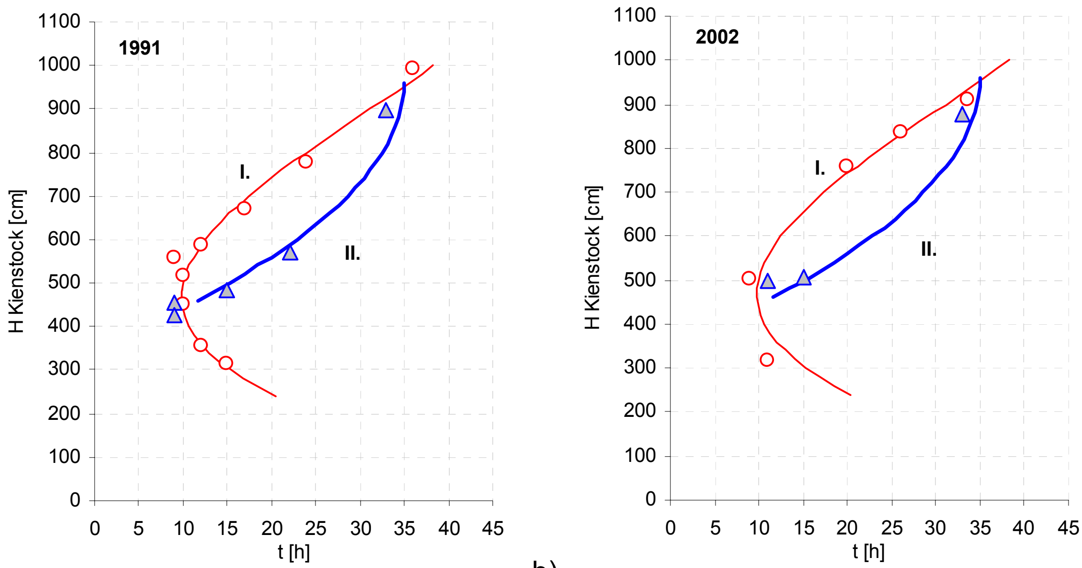
Figure 5 Water levels in stations Danube: Kienstock and Danube: Bratislava with corresponding points for estimation of the travel time of increasing (squares) and decreasing (triangles) waves, a) 1991 flood, b) 2002 flood.

<u>March 2002 flood</u>

The increase of discharge during the March 2002 flood was even steeper than in 1991. The water level in Kienstock raised from 407 cm to 597 cm within 6 hours (Figure 5b). The steep increase of water level in upper Danube was caused by rich rainfall of 95-120 mm during 3 days in German and Austrian Alps. The oceanic arctic air mass arrived after 3 days from the North and brought cooling. Snow precipitation did not contribute to runoff fortunately, otherwise the flood wave in Bratislava could reach 10 000 m^3s^{-1}. Maximum measured water level in Kienstock was 910 cm (22.3. 24:00 h), and in Bratislava 871 cm (24.3. 7-10:00 h). The discharge in Bratislava corresponded to 17-year flood (Mitkova et al, 2002; Szolgay & Kohnova, 2001).

In Figure 6a there is the relation of travel time τ (Kienstock – Bratislava) to water level in Kienstock for corresponding points of increasing and decreasing wave in 1991 (non-storage routing method). The travel time Kienstock – Bratislava in 2002 was estimated analogically to 1991. The hourly water level data were used. The travel time of the 2002 flood has not changed compared to flood wave 1991, therefore the relations (4) and (5) can be used for forecast (Figure 6b).

In case of water level is the situation quite different. The corresponding water level at the same discharge is much higher in 2002. The 1991 flood culminated with discharge of 9430 m^3s^{-1} and water level 859 cm. In 2002 the measured water level 871 cm corresponded to discharge of 8474 m^3s^{-1}. In Figure 8 we can see that the Q_{50} (about 10 000 m^3s^{-1}) water level at Bratislava in recent conditions will be about 950 cm (III. stage of flood activity).



a) b)

Figure 6 Travel time Kienstock – Bratislava for increasing (I.) and decreasing (II.) wave. a) 1991 flood; b) 2002 flood.

2.1 Derivation of the empirical relationships for estimation of the water level in Bratislava

The non-storage routing method is based on description of the flood wave propagation in river channel and allows to estimate the water level H in lower station from water level in one or more upper stations. The following relation is directly used when forecasting:

$$H_{d,t+\tau} = f\,(H_{h,\,t}) \tag{6}$$

where: $H_{d,t+\tau}$ – water level in forecasting station after travel time τ since t;
$H_{h,t}$ – water level in upper station in time t.

For derivation of the relation (6) the same input data were used as in case of travel times. Linear relationship was used for estimation of the relation between corresponding water levels:

$$H_{d,t+\tau} = b\,H_{h,\,t} + a \tag{7}$$

Following linear relationship was found for Ybbs – Bratislava section in 1991–1999:

$$H_{d,t+\tau} = 1.1121\,H_{h,\,t} - 9.3384 \tag{8}$$

For Kienstock – Bratislava in 1991–1999 is valid:

$$H_{d,t+\tau} = 0.9245\,H_{h,\,t} - 18.522 \tag{9}$$

The water levels increased in Bratislava after 1992 due to Cunovo backwater and sedimentation in river channel. Therefore, we tried to find the change in relation between peak water levels in Kienstock and Bratislava in 1991–1995 and in last 4 years 1999–2002. Relation of the water levels in both stations is in Figure 7.

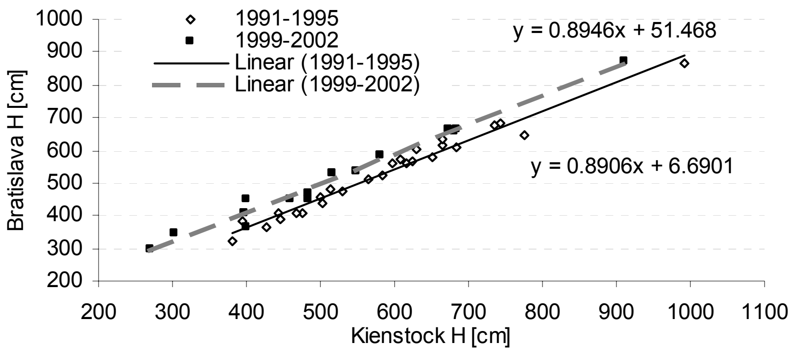


Figure 7 Relation of peak water levels in Kienstock and Bratislava, comparison of two periods 1991–1995 (39 waves) and 1999–2002 (19 waves).

The relations are described by following equations:

Period 1991–1995

$$H_{BA,t+\tau} = 0.89\ H_{KI,\ t} - 6.69 \tag{10}$$

where: $H_{BA,t+\tau}$ – water level in Bratislava in time t+τ [cm];
$H_{KI,t}$ – water level in Kienstock in time t [cm].

Period 1999–2002

$$H_{BA,t+\tau} = 0.894\ H_{KI,\ t} + 51.5 \tag{11}$$

kde: $H_{BA,t+\tau}$ – water level in Bratislava in time t+τ [cm];
$H_{KI,t}$ – water level in Kienstock in time t [cm].

The derived equations show the difference in relation between water levels in Kienstock and Bratislava in 1999–2002, and 1991–1995, respectively. At the water level of 800 cm in Kienstock the increase of water level represents + 61.5 cm in Bratislava in the recent period (Figure 8). Similar difference can be found in consumption curve valid in 1991. The difference in water levels in respective periods can be assigned to recent sedimentation in the river channel and to backwater effect of the Cunovo dam. The backwater goes up to Austrian border in rkm 1873 near Wolfsthal during low flows.

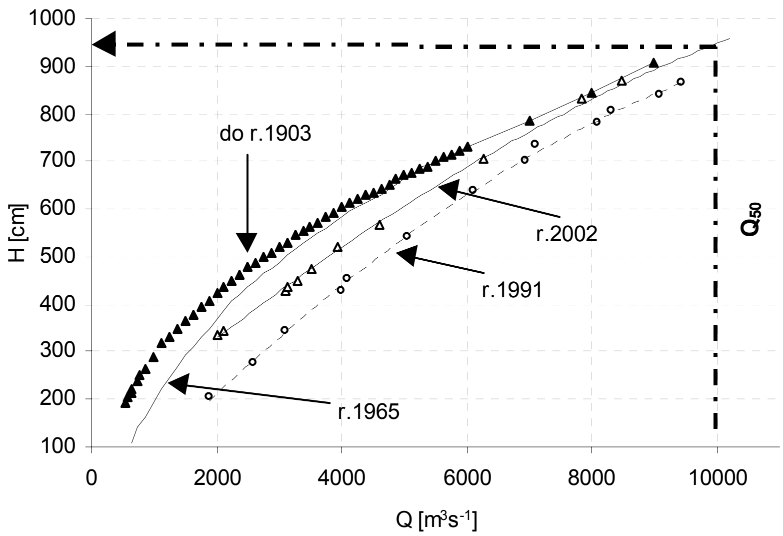


Figure 8 Changes of relation between discharge and water level in Bratislava. Consumption curve valid to 1903 and in 1965 according Zatkalik (1970). Comparison of floods in 1991 and in March 2002.

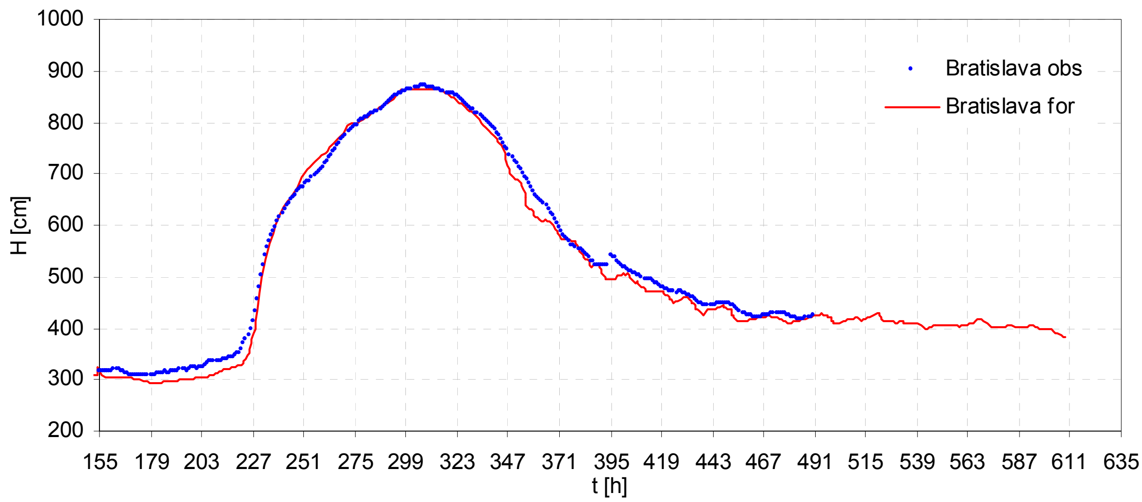


Figure 9 Verification of the non-storage routing model REMOD for Danube water level forecast in Bratislava using flood wave of March 2002.

3 Forecast of the water level and discharge

3.1 Forecast of the water level in Bratislava by regression model REMOD

The simple non-storage routing model **REMOD** (**R**egression-**E**mpirical **MO**del **D**anube) for forecast of Danube water level in Bratislava from hourly water levels in Kienstock was compiled on base of the equations (4), (5) and (11). As the flood wave travel time Kienstock – Bratislava varies between 10 and 35 hours, also the forecast is within this range. If we want to forecast the water level in Bratislava 24 hours ahead and the expected travel time is 15 hours, we must use the water levels forecasted for Kienstock station.

The quality of the model forecast can be seen in Figure 9, where are both measured and forecasted water levels in station Danube: Bratislava during the March 2002 flood. The forecasted water levels were underestimated and relation (11) was updated to (11'):

$$H_{BA,t+\tau} = 0.87\ H_{KI,\ t} + 72.7 \qquad (11')$$

3.2 Forecast of discharge by NLN - Danube model

Model NLN - Danube is aimed at simulation of flows in Danube River between Ybbs and Nagymaros in six sections 1. Ybbs – Kienstock; 2. Kienstock – Devin; 3. Devin – Medvedov; 4. Medvedov – Iza; 5. Iza – Sturovo; 6. Sturovo - Nagymaros. Model of each part (each section) of the simulated system is based upon the concept of a series of equal nonlinear reservoirs, thus belonging to the category of hydrological conceptual nonlinear models. Model input (P) represents the input into the first reservoir of the cascade, its output is the input into the second one in series, etc., and the output from the last reservoir is the output (Q) from the model of that section. Both input P and output Q are expressed in discharge units [e.g. m^3s^{-1}], the storage V is volume [m^3]. Number of reservoirs in the cascade (N) is one of the model parameters (Svoboda et al., 2000; Pekarova et al., 2001).

Other parameters define the shape of each of the routing curves of the reservoirs in series, describing the reservoir output in relation to its storage (V), as:

$$Q = B.V^{EX} \qquad (12)$$

where: *Q* - reservoir output;
V - volume of reservoir [m^3];
EX - the nonlinearity parameter;
B - the proportionality parameter.

The flood wave propagation is modelled in equidistant discrete time steps *0, 1, 2, … M*. The difference between two steps is given by parameter ΔT. In time steps i and $i+1$, for known input P_{i+1} and output Q_i , the unknown output Q_{i+1} is determined from the continuity equation within the time interval $i+1$ of the length ΔT as:

$$(P_{i+1} - Q_{i+1}).\Delta T = V_{i+1} - V_i \tag{13}$$

where: P_{i+1} , Q_{i+1} - is the average input/output of the interval $i+1$;
V_{i+1} , V_i - are storages at the interval $i+1$ and i.

From equations (12) and (13) we receive

$$(P_{i+1} - Q_{i+1}).\Delta T = \frac{Q_{i+1}^{1/EX} - Q_i^{1/EX}}{B^{1/EX}} \tag{14}$$

The equation (14) defines the non-linear function *f* of one unknown, Q_{i+1},

$$f(Q_{i+1}) = (P_{i+1} - Q_{i+1}).\Delta T - \frac{Q_{i+1}^{1/EX} - Q_i^{1/EX}}{B^{1/EX}} \tag{15}$$

which is searched by linearisation (Newton) method

$$Q_{i+1}^{(k+1)} = Q_{i+1}^{(k)} - \frac{f\left(Q_{i+1}^{(k)}\right)}{f'\left(Q_{i+1}^{(k)}\right)} \tag{16}$$

what gives in our case the iteration formula

$$Q_{i+1}^{(k+1)} = Q_{i+1}^{(k)} + \frac{(P_{i+1} - Q_{i+1}^{(k)}).\Delta T - \left[(Q_{i+1}^{(k)})^{1/EX} - (Q_i)^{1/EX}\right]B^{-1/EX}}{\Delta T + (Q_{i+1}^{(k)})^{(1-EX)/EX}.B^{-1/EX}.EX^{-1}} \tag{17}$$

The parameters of the transformation curve shape are expressed by ratio parameter B,

$$B = \left(\frac{N.\Delta T}{BK}\right)^{EX}, \tag{18}$$

where: N - number of storages in one section of the model;
BK - "time constant" of an equivalent linear system.

The iteration process (17) is performed with accuracy of 0.001.
Example of the NLN - Danube model output is in Figure 10 for the March 2002 flood. The comparison of measured and forecasted values for Bratislava station is in Figure 11.

Conclusion

The transformation properties of the Danube river channel are changing due to anthropogenic activities. It influences the flood travel times and also flow behaviour during passing of the flood wave through the channel. The tributaries of Danube react more quickly on the rainfall input or snowmelt water in the starting phase of the flood. Such development makes the short-time forecasts on upper Danube more difficult. This process is not finished and it will be necessary to update the forecasting methods permanently.

The results show that the travel times of 1991–2002 are shorter by about 41% compared to 1923–1966 and by about 11% compared to 1975–1991. The travel times of 1991 flood and 2002 flood did not change significantly and the relations (4) and (5) could be used for forecasting recently.

The situation is different in the case of water levels. Water levels in Bratislava in 2002 are much higher at the same discharge. E.g., the 1991 flood culminated with discharge 9430 $m^3.s^{-1}$ at water level 859 cm. In 2002 the discharge was 8474 $m^3.s^{-1}$ and the water level was 871 cm. It is probable, that at the 50-year flood (about 9 750 $m^3.s^{-1}$) the water level in

Bratislava will reach about 950 cm in recent conditions. It corresponds to the III. stage of flood activity in Bratislava profile.

The equations (4), (5) and (11) were used to compile a simple regression model REMOD for water level forecast in Bratislava from hourly water levels in Kienstock. The model was verified on 2002 flood. Efficiency of the model is necessary to test on longer period. The influence of Morava river will be included into equation (11) in next step to improve the forecast of Danube water levels in Bratislava.

Model NLN - Danube was used to simulate the discharge in section Kienstock - Nagymaros during the flood. The simulation of hourly discharge was based on measured hourly water levels. The discharge in Kienstock was obtained from hourly water levels using the valid consumption curve. The contribution of the Danube left-side tributaries Morava, Vah, Hron and Ipel was included into the model.

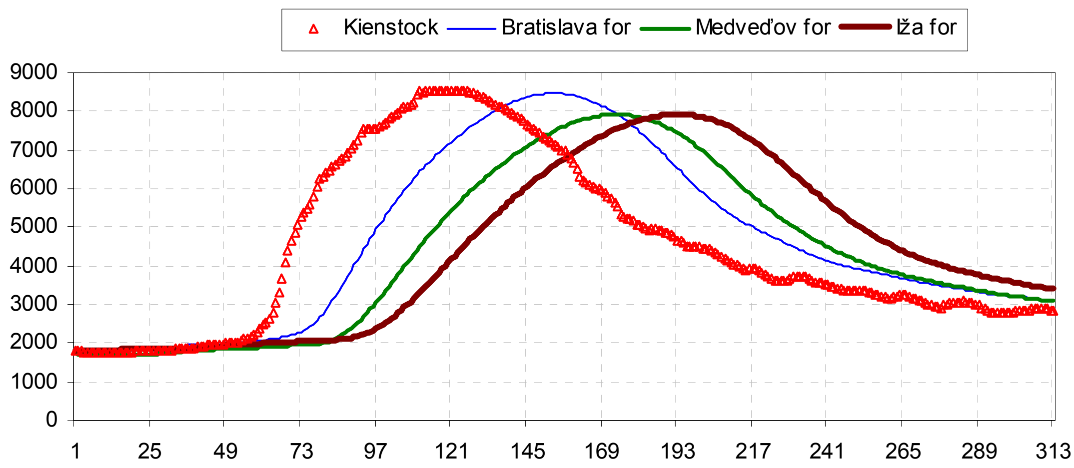


Figure 10 Forecast of floods wave in March 2002 between Kiestock and Nagymaros, nonlinear routing model NLN - Danube model, Kienstock - measured data.

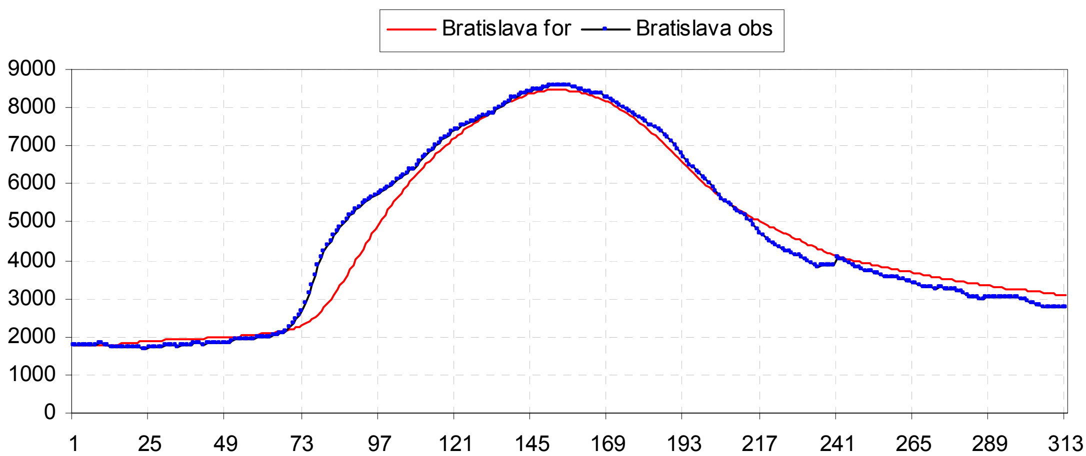


Figure 11 Comparison of forecasted and observed hourly discharge of floods wave in March 2002 at Bratislava station.

Acknowledgement

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