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MODELLING THE HYDROLOGICAL EFFECTS OF A LEVEE FAILURE ON THE LOWER TISZA RIVER

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Abstract

Along the Lower Tisza River (Hungary) the water level of the floods reached new record stages in 1998 and 2006, resulting in 80 cm increase in the peak flood level since the “great flood of 1970”. Due to the gradual weakening of the levee-system caused by the several long-lasting floods, the question has arisen, that as in case of a levee breach or failure how would it modify the hydrological parameters of the river. The aim of the research is to create a hydrological model to analyse the effects (as stage reduction, slope and stream power) of two different levee breaches: one happening before the peak of the flood and another at the time of the flood level. The simulated levee breaching happened on the Tisza River at Mindszent, and the data-set of the 2006 flood was used for the modelling (at that time no levee failure happened in Hungary, and it was the greatest flood in history).

In the simulation the levee was broken at a point, where the channel is very close and intensively eroding, thus there is a real risk of a levee failure. If the levee would be broken a well defined area (reservoir) would be flooded, surrounded by the secondary levees and the rim of the high floodplain. During the simulation the HEC-RAS 4.1. ArcGIS 10.1 and HEC-GeoRAS software were applied.

The greatest changes in the hydrology of Tisza occurred in the cross section where the levee breached, though the effects propagated upstream and downstream too. Due to the water outflow from the Tisza the greatest stage reduction effect was 1.54±0.1 m. The slope conditions changed too, as it increased from 4 cm/km to 6.5 cm/km in the upstream reach, while downstream of the failure point it decreased from 3.5 cm/km to 1.9 cm/km. At the same time the stream power increased from 4 W/m to 5.5 W/m in the upstream section, while it decreased from 3.5 W/m to 1.5 W/m in the downstream reach. Comparing the results of the simulations at different stages (one at the highest stage and one at 1.0 m lower stage) it seems that the hydrological parameters did not change considerably (1%), though in a case of a levee failure at higher the reservoir reached the maximal water level sooner, though less water was stored in it, as the fall of the river was continuous.

Keywords: levee failure, flooding, HEC-RAS, flood modelling, hydrologic parameters

INTRODUCTION

Nowadays floods are the most common in natural hazards, and they cause the greatest economical losses, moreover they endanger the life of millions of people living on the flood-prone areas along rivers, especially if the inundation is a result of unexpected incidences, for example a levee or a dam failure (Yalcin and Akyurek, 2004). Every levee breach or failures carries human tragedies and considerable losses, therefore it is important to develop detailed plans for flood-prevention and to carry out hydro-dynamic modelling of catastrophes.

On the Tisza River, which is the greatest tributary of the Danube, the flood levels have been dangerously raised on several sections since the “great flood of 1970”, thus the flood hazard and risk increased. The seriousness of the problem is well-demonstrated by the fact that between 1998 and 2010 period the peak flood level reached new records twice, increasing the record stage by 80 cm compared to the 1970 peak flood. According to the engineers the solution of the problem of the decreasing high water levels could be the construction of flood control reservoirs that can decrease the peak flow of floods (Szigyártó and Rátky, 2010).

The Cigánd Reservoir (storage capacity: 94 million m^3) was the first flood storage reservoir built on the Upper-Tisza. If it would be opened and filled up to its maximum capacity, it would decrease the flood stage by 0.25 m [1]. Concerning the plans and the construction of this reservoir Szigyártó (2012) expressed several critiques, as the inflow capacity of the storage lake reaches only 65 % of the required capacity. Another flood reservoir was built between the Szamos and Kraszna Rivers (capacity: 126 million m^3) in 2014, and the Bereg Reservoir is planned to be finished at the end of 2015. The Upper Tisza flood control system continues in the Middle Tisza too, where the Tiszaroff (97 million m^3), the Nagykunság (99 million m^3) and the Hany-Tiszasüly Reservoirs (247 million m^3) were built. As the sum-effect of the operation of all these reservoirs the flood level could be reduced by 0.5-0.6 m along the river according to model calculations [1]. However, considering the flood level increase (0.8 m) since 1970, it is not enough to reduce the flood hazard effectively. Thus, we believe, that this would only be a partial solution of the problem, since the management of the floodplain (decreasing the vegetational roughness) and the widening of the tight sections are also needed.

The application of models in hydrology has been started in 1960's, by simulating the flow conditions in a channel and the seepage in porous materials (Whisler and Watson, 1968). By the 1990's software groups were developed, that can model complicated hydrological systems and situations, and they have been widely applied in water management issues. Nowadays the developed models able to simulate most of the hydrological processes in various conditions, but it still remains a question, what is the relation between the results and the real nature, since numeric models provide correct results, if the initial conditions and the border conditions were chosen properly. However some empirical parameters (e.g. vegetational roughness, morphological roughness) cannot be determined easily and properly, though they have significant role in modelling, which can greatly modify the results.

One of the most widespread model in hydrological modelling is HEC-RAS (Hydrologic Engineering Center-River Analysis System). This is an one dimensional and linear model which is able to produce pseudo 3-D image with the correct ordering of cross-sections. The software is suitable to make calculations for sub-critical (Froude number <1) or for super-critical (Froude number >1) hydrodynamic situations besides this it is possible to build in the model detailed hydraulic constructions and structures. Novelty of the HEC-RAS software is that it divides the cross-sections into main channel, left and right floodplain zones and it calculates the velocity and discharge for these zones, and the program finally summarizes the data. The model calculate is able to calculate water level for each cross-sections, so in the separate branches not appear locally evolved higher or lower water levels (HEC-RAS Hydraulic Reference 2010). The input datasets of the HEC-RAS model are the following: geometric data of the riverbed, of engineering structures (bridges, culverts etc.), water level and discharge curves, roughness parameter (Pregun, 2009) which can be determined by empirical, mathematical or statistical methods (Kamanbedast and Esfandiar, 2011).

Between the HEC-RAS and ArcGIS software the connection is established by HEC-GeoRAS, a toolset of ArcMap program. It combines the digital elevation data with spatial analysis, thus the visualization of flood-depth and velocity characteristic becomes possible. The toolset could display the flooded areas on the digital elevation model, flood losses could be estimated, maps and illustrations cold be combined.

The MIKE hydraulic modelling family has been developed since the 1970's. The input data are similar to HEC-RAS's (MIKE 11; Józsa, 2001; Karatzas et al., 2012), but it is appropriate to study the Manning roughness in time and space, and it enables inundation simulation in 1D and 2D (MIKE 21) even various environments, as in rivers, cities, sewer systems, coastal areas and dam breaches. Moreover the models can be used at different scales from local to regional [2].

The aim of our research is to model and analyze the hydrological effect of a levee failure by Mindszent on the Lower Tisza River. The possibility of a levee breaching or failure is increasing by time, because (1) the repeated and long-lasting floods weaken the levee; (2) the water level of floods will probably increase further, thus it may cause overtopping; and (3) mass-movements endanger the levees, as where the levee was built too close to the channel, revetments were created to stop the lateral erosion, however during the last 50-80 years the channel intensively incised (Kiss et al., 2008) and the revetments were partially destroyed, thus the lateral erosion could endanger the levees. The simulated levee failure took place where in reality it is the most probable: at the given point (at Mindszent) the levee is very close (20-25 m) to the river channel, and the revetment is destroyed by landslides. In the HEC-RAS model we used the data of the 2006 flood as a basis, as it was the last record flood in the region. During the research we aimed to simulate and compare the hydrological effects (as stage reduction, slope and stream power) of two different levee breaches: one happening five days before the peak of the flood and another at the time of the peak flood level. The results that are gained by the modelling of a levee failure could provide useful information for the flood control reservoir that is planned on the Lower Tisza too.

STUDY AREA

The Tisza River is the second largest river in Hungary (L: 962 km, A 157.200 km^2; Lászlóffy, 1982), its lower reach was chosen for the study (Fig. 1). The regime of Tisza is influenced by the diverse climatic characteristic of the catchments and the tributaries with frequently extreme regime. Floods mostly develop at early spring due to snow melt and rainfall, and at the beginning of summer (Lászlóffy, 1982). On the study area the swelling effect of Danube could also be detected (Vágás, 2003; Bezdán, 2011). The characteristics of the study area is that the measured water level record in 1970 has been exceeded in 2000 (1000 cm) and in 2006 (1062 cm) too, and the durability of floods continuously increases (Kovács, 2007; Sándor, 2011). The low stages also last longer, but along the Lower Tisza this phenomenon is moderated by the Törökbecse Barrage. The difference between the lowest (70 m^3/s) and the greatest (4200 m^3/s) discharges is sixty-fold.

During the simulated levee failure the flood flowed outside of the present-day active floodplain, into the western protected side (it is called storage area/lake in the text below). The storage area has well defined borders: secondary artificial levees are found in north and south, in east is the main levee of the Tisza, and in west the natural rim of the high floodplain could be found. Thus, the flooded area is actually a natural low floodplain, which was evolved in the Pleistocene and Holocene. There is 3-5 m difference between the low and high floodplains (Her-

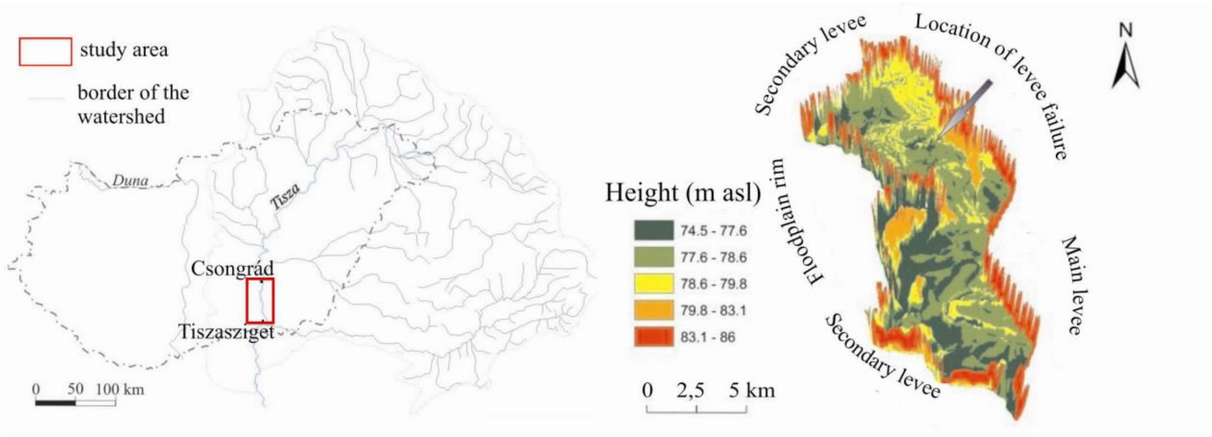

Fig. 1 The study area is located on the Lower Tisza. In the model the flood would destroy the levee and inundate a flood protected area (reservoir)

nesz and Kiss, 2013). On the surface of the storage lake 1.5-2 m deep paleo-channels are which could lead the flood wave into the storage area and out, however after the regression of the flood stagnant water would remain in these forms for a while. Point-bars, crevasses and floodplain islands rise from the low floodplain also characteristic of this area (Kiss et al., 2012). Before the 19th c. regulation works the low floodplain was periodically flooded, therefore settlements have been established just on the high floodplain or on floodplain islands. The levees in the area were built in the 1880's and were raised several times (Schweitzer, 2003).

The inundated area used in the model could serve as real a flood storage reservoir, however the levees around should be heightened up to a uniform level.

METHODS

For the research we used the dataset of the 2006 flood, which was calibrated by the Lower Tisza Hydrological Directorate under HEC-RAS software. This flood was the highest flood in history, when the water level reached 1062 cm, thus 5.0-5.5 m deep water covered the floodplain for over 80 days.

The model was uploaded by large amount of data: hydrological and morphological data of the main channel and the tributaries, cross-sections, bridge data, roughness values and the data of Törökbecse Barrage. The boundary conditions of the model had to be set out of the study area, because the simulated levee should not affect the boundary conditions and the starting calculation failures could be corrected. When the boundary of the model was set, it had to be considered, that (1) the Tisza has very low slope in the study area (1-6 cm/km; Kovács, 2007), and (2) during a previous levee failure in 1879 the flood level was reduced by 1 m. Thus we assumed that the levee breach by Mindszent (218 fkm) would have an affect at least on a 50-50 km-long reach downstream and upstream. Therefore, the upper boundary of the model was set by Szolnok (334.6 fkm) and the lower boundary by Titel (11.6 fkm). Along the modelled reach the Körös and Maros Rivers flow into the Tisza, therefore their data were aldso built in the model. The boundary of the Maros River reach set Makó (24.3 fkm) of the Körös River by Gyoma (79.1 fkm).

For the simulation we had to add the cross-sections of the channel. It was surveyed by the Lower Tisza Hydrological Directorate at every 100 m. However in order to model the levee breach the intervals between the cross-sections around the breach had to be decreased, using the *XS inerpolation* tool in HEC-RAS. We added 30-30 interpolated cross-sections both in upstream and downstream along a 200 m-long reach. After setting the geometrical parameters the hydrological boundary conditions in the *Unsteady Flow Simulation* menu point had to be adjusted. The stage data were measured hourly, while the discharge data were mostly calculated from the water stages and some were actually measured. The gate operational data of Törökbecse Barrage (at 61.79 fkm) were also filled into the model.

In the next step the inundated storage area had to be defined surrounded by the levees and the floodplain rim. We used the digital elevation model of the area with 2*2 m resolution with HEC-GeoRAS toolset. The HEC-RAS software able to calculate the inundation of the area, creating its volume curve extracted with the help of *Elevetion Range* and *Elevation Volume Data* tools found in the HEC-GeoRAS toolset. The *Elevation Range* tool determines the altitude of the deepest and the highest points. The *Elevation Volume Data* tool contains volume values related to different elevation categories (Table 1). After creating these data the storage area had to be exported using the RAS Data tool, and then the storage area had to be imported into the HEC-RAS geometry dataset.

The levee was built into the model as a lateral structure, because in this way a levee breach could be initiated. The geometry data of the levee were uploaded, and we set on that reach and the river kilometre on which the starting point of the levee should have been placed. Furthermore, we joined the levee with the right bank and set the water would flow into the storage area on the protected side in case of levee breach. The width and the height of the levees were set in the *Lateral Weir Embankment* menu point and the distance from the upstream cross-section in the *Weir Stationing* menu point.

Table 1 Required data for filling up the storage area

Height (m asl)	Volume (m^3)	Area (ha)
–74.5	0	10890
74.51–74.56	522.70	10890
74.57–74.64	1317.47	13335
74.65–74.72	2227.90	16895
74.73–74.83	3814.74	21065
74.84–74.96	6242.60	26005
74.97–75.11	9773.72	32625
75.12–75.30	14956.79	38285
75.31–75.52	22415.91	68235
75.57–75.78	39571.46	97765
75.57–76.10	122167.22	885775
76.11–76.48	474995.47	1484965
76.49–76.94	2279174.25	6473645
76.95–77.49	8573056	19036124
77.50–78.15	30234490	64933576
78.16–78.94	86709024	109962880
78.95–79.89	182364640	132163272
79.90–81.03	307073664	140241056
81.04–82.39	460514816	141567792
82.40–84.03	646742528	142157424
84.04–86.0	870831232	142212288

The modelled levee breach or failure was created by Mindszent (218 fkm), where the levee is very close to the river (20-25 m), the revetment have been partly destroyed and the levee is threatened by landslides. Besides, the area behind is the deepest part of the simulated storage lake, thus the paleo-channel which starts exactly at the levee failure point could control the inflow and outflow of the flood. The simulated levee breach would totally destroy the levee along its 60 m length within 6 hours with an even rate. The steepness of the breached surface is 1-1° on the left and on the right side therefore the breached surface has trapezoid shape. The coefficient of the levee material was set to 2.6, considering that it was built of soil and loose sediments. As we aim the simulation of two levee failures, in the first case the levee breach occurred at 958 cm flood level (equals to 84.4 m altitude, or 1 m before the peak stage) and in the second case by the levee failure happened at the highest stage at 1058 cm (85.3 m altitude).

After adjusting the boundary and the initial conditions the *Plan Data* was compiled by selecting that geometry and unsteady simulation file that should have been used during the simulation. The initial (2006.03.22. 7:00) and the final (2006 5.31 7:00) dates were also set in the Plan Data window. This period cover the whole duration of the 2006 flood.

The *Hydrograph Output Interval* menu records water stage and discharge values into a file in given time intervals. As the water level measured in every hour at the gauging stations, 1-hour interval for the output was selected.

The results of the model were validated using the measured data of the 2006 flood. During the process the values calculated by the model and the real measurement data were exported into an EXCEL table. The accuracy of the model was ±0.1 m within the studied period, however during the last ten days of the falling stage the error became as high as ±1.0 m, which could be explained by the special characteristics of the 1-D model.

RESULTS

Levee failure prior the peak flood (at 958 cm)

If during the 2006 flood the levee would have been breached at Mindszent at 958 cm stage, and the flowing water would erode a 60 m wide opening on the levee in six hours, the maximum discharge of the out-flowing water would be 1255 m^3/s (Fig 2). The flood storage area (113,7 km^2) on the protected side of the levee would be filled up to 84.5 m asl. At the end of the process ca. 700 million m^3 water would flow into the reservoir. The greatest volume would be stored on the 13th day after the levee breach, as afterwards the water would start to flow backwards to the Tisza.

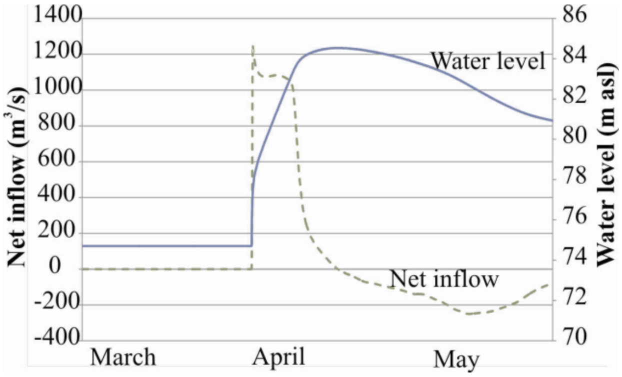

Fig 2 The water level and the water inflow curves of the reservoir in the case when the levee breached before the peak-flood at 958 cm stage

Comparing the simulated water stages of the neighbouring gauging stations to the 2006 stage data (without levee failure) it could be stated, that the maximum stage-reduction effect is 1.54±0.1 m at the Mindszent (218 fkm) gauging station (Fig 3). At the Tiszasziget gauging station (167 fkm) ca. 50 km downstream from the levee failure this effect decreases to 1.2 ±0.1 m, while upstream at Csongrád (246 fkm) it is only 0.68±0.1 m respectively. The greatest degree of stage-reduction appears on almost all gauging stations on the same day, 6 days after the levee failure.

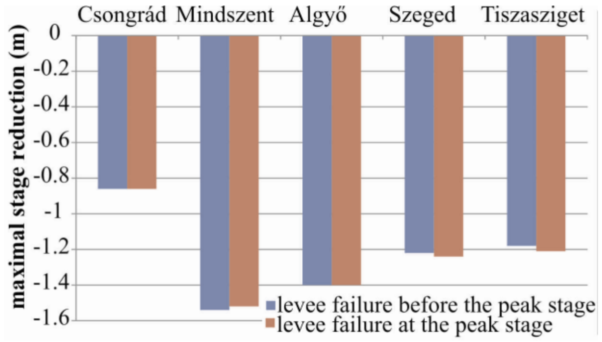

Fig 3 Maximal stage reduction effect of the two simulated levee failures

The simulated hydrograph reflects stage drop by approximately 50 cm on the day after the levee failure, though after 6 days the stage increases again and reaches a peak at 965 cm, which level is 7 cm higher than the water level when the levee breached (Fig 4). The maximum height difference between the simulated hydrograph and the real stage curve of the 2006 flood is the greatest at Mindszent (0.78±0.1 m), and it decreases upstream and downstream, in the function of distance from the point of the levee failure.

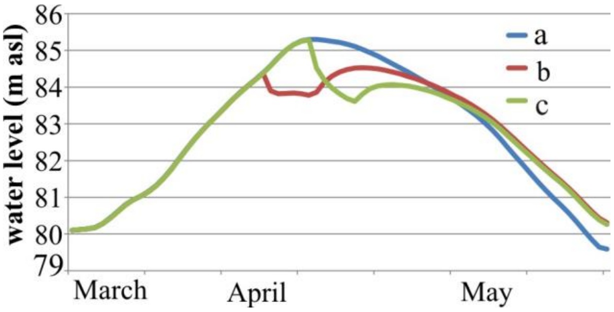

Fig 4 Hydrographs of the 2006 flood (a), of the simulated flood with levee failure at 958 cm stage (b), and of the simulated flood with levee failure at 1058 cm stage (c)

After the peak stage the water level drops. Simultaneously, the water level in the reservoir falls too, due to back-flow towards the Tisza. This increases the stage of the Tisza by up to 0.79±0.1 m at the cross-section where the levee failure occurs. In the last 10 days of the simulation the model counted by greater error (±1.0 m), therefore only the existence of the phenomenon of water level rising could be proved, but exact values of the process and the emptying of the reservoir within the simulated time interval could not be studied in detail.

Based on the calculations of the simulated levee failure the average slope of the Tisza increases from 4 cm/km to 6.5 cm/km on the upstream section between Csongrád and Mindszent, while on the downstream section it decreases from 3.5 cm/km to 1.9 cm/km (Fig. 5). At the same time the stream power of the river on the upstream section increases from 4 W/m to 5.5 W/m, while it decreases on the downstream section. The greatest decrease from 3.5 W/m to 1.5 W/m was calculated by Mindszent (Fig. 6).

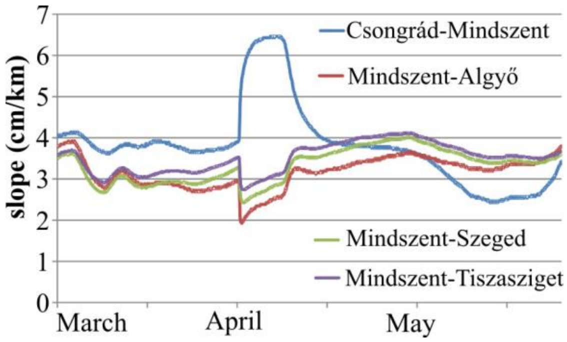

Fig 5 Slope changes of the Tisza River after a levee failure at Mindszent

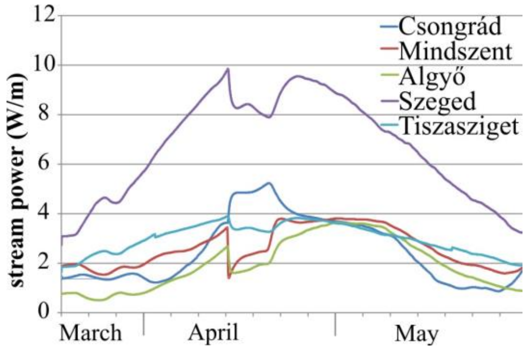

Fig 6 Stream power changes of the Tisza River after a levee failure at Mindszent

Levee failure at the peak of the flood (1058 cm)

In the second simulated case the levee failure would occur at the peak of the flood (1058 cm), and the levee would be destroyed along a 60 m long section. In this case the maximum discharge of the outflow (Fig. 7) would be much higher (1698 m^3/s) than in the previous case (1255 m^3/s), therefore the reservoir would be filled up in 11 days (shorter by 2 days) up to 84 m asl, which is 0.5 m lower than in the first case. Altogether 650 million m^3 water would be stored in the reservoir, less by 50 million m^3 than during the first simulated levee failure. It could be explained by the different hydrographs of the two cases: in the first case the levee breaches 1.0 m before the peak flood, thus the outflow got high amount of water supply for another 6 days, until the flood starts to fall. However, in the second case the levee failure occurs at the peak of the hydrograph, thus the falling limb of the flood supplies less water, thus the amount of outflow decreases too.

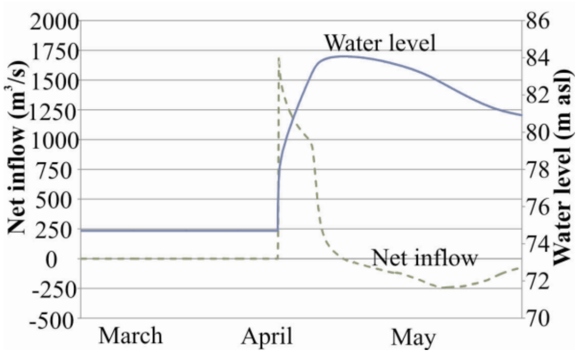

Fig. 7 The water level and the water inflow curves of the reservoir in the case when the levee breached at peak-flood

The maximum values of the diminution effect of the two simulated levee failures do not change significantly (1%), so the diminution effect would be 1.54-1.52 m (Fig. 4). During the second simulation the maximum value of diminution appears 5-6 days after the levee failure, which is one day shorter than in the first simulation case. The backflow into the Tisza would be very similar as in the first simulated case.

Comparing the simulation of the levee breach at the peak of the flood with the simulation of the levee failure at 1.0 m lower stage, it seems that the changes in slope are not significant (<1%). Although the slope on the upstream (Csongrád–Mindszent) section increases to 6.3 cm/km, which is slightly lower than it was during the former simulation. On the downstream section between Algyő and Mindszent the slope decreases to the same value (1.9 cm/km). Considering the stream power the trends in both cases are similar, as it increases considerably on the upstream section from 3.3 W/m to 5.5 W/m, while downstream of Mindszent it reduces significantly from 4.1 W/m to 1.4 W/m.

DISCUSSION

Usually levee failures occur due to levee overtopping, as it happened during the most disastrous Hungarian floods of the Tisza: in 1879 Szeged was destroyed by the flood, or in 2001 a levee failure by Tarpa destroyed several settlements in the Upper Tisza region. So in the second simulation we supposed overtopping, however in the first case we simulated a levee failure that occurred at 958 cm water stage, so at 1.0 m lower stage than the peak of the flood. In this simulated case overtopping is impossible, but the slide of the levee is very probable, as landslides endanger the levee due to very active incision of the channel. Besides, the results of this simulation could be applied if the levee would be opened consciously with flood-protection purposes, so the protected side could be used as a flood control reservoir.

After the levee failure the filling up of the reservoir area would be controlled by the hydrology of the flood wave and the characteristics of the relief. In the model the initial point of the filling up is the deepest point of the area, however it could be considered as the gross error of the model, since in reality the filling up does not begin at the deepest point, but at the site of the levee failure. Thus, applying the HEC-RAS only the hydrological changes of the Tisza could be simulated.

The water outflow into the protected floodplain area changes significantly the hydrological parameters of the Tisza. The greatest changes occur at the cross-section of the levee failure (Mindszent, 218 fkm), as the largest flood diminution effect (1.54±0.1 m) could be observed here. Towards downstream the effect would decrease, so at Tiszasziget (50 km far from Mindszent) the maximum diminution effect would be just 1.22±0.1 m (Fig. 3–4). The small difference could be explained by the small slope (1.9-3.5 cm/km) of the river. The levee breach also causes flood diminution towards upstream, however its degree is reduced by the arriving flood wave.

Comparing the hydrographs with and without levee breach the date and the degree of the maximum diminution effect could be determined. The simulated levee breach (at 958 cm stage) occurred on April 16th and the greatest diminution effect ensued six days afterwards along the middle section of the river (Mindszent–Algyő–Szeged), but it developed one day later at the further gauging stations (Csongrád and Tiszasziget). The temporal coincidence of the maximal diminution effect on the gauges could be explained by two reasons. First of all the effect of the levee breach is pronounced for 6-8 days until the outflow-discharge (towards the reservoir) is over 1000 m^3/s, thus great part of the floodwater supply coming from the upstream is drained off. On the other hand, the peak of the 2006 flood occurs exactly 6-8 days after the levee breach so the diminution effect coincides with the duration of the rising limb of the arriving flood-wave.

The date of the peak of the 2006 flood without levee breach (at Mindszent April 22nd) precedes the date of the peak of the flood with levee breach at 958 cm stage (at Mindszent April 28th). It could be explained by the fact that the out-flowing water from the Tisza is able to decrease the water stages of the river only at a particular discharge (in this situation 1000 m^3/s) and only for a certain time (in this case for 6-8 days) against the water supply from upstream. After the reservoir is filled up, the amount of inflow water decreases, and the diminution effect terminates.

The occurrence of a levee failure has the greatest probability at the peak of a flood. Comparing the values of the two simulations it seems, that in case of the peak-stage levee failure the processes are more rapid. Thus, (1) the out-flowing discharge increases by 35%, (2) the filling up of the reservoir lasts 2 days shorter, (3) the water level in the reservoir is 0.5 m lower due to the falling stage of the Tisza and the resulted decreasing water supply, and (4) in the reservoir the amount of stored water is less by 50 million m^3. These processes are reflected on the hydrographs of the out-flowing water (Fig. 2 and 7): the hydrograph of the out-flowing water of the levee failure at peak-flood decreases steeper, since the water supply from the river is becomes limited. However, between the two simulations the values of the greatest stage reduction does not change significantly, probably because in both cases almost the same amount of water flows out to the protected side. The maximum stage reduction occurs one day earlier in case of the second simulation (at peak-flood), which is probably in connection with the higher stage (thus higher local slope) and the greater out-flowing discharge.

The slope conditions within the main channel are greatly affected by the levee failure and the out-flow, though there are only slight differences between the two scenarios. This similarity could be explained by that the stage reduction in the two cases reached almost the same degree.

The stream power highly depends on slope and discharge. Thus in case of a levee failure the slope increases on the upstream section of the levee failure, therefore the stream power increases considerably, whilst on the downstream section it decreases. (In the case of Szeged the Maros River also influences the stream power locally, therefore the simulation resulted much higher stream power values.) The changes in slope and stream power values are in connection with distance from the location of the levee failure, as by increasing distance the effect decreases.

CONCLUSIONS

The aim of the presented research was to analyze the hydrological effect of a possible levee failure by Mindszent, when the western levee would breach (or opened consciously) along 60 m length and the flood would inundate a confined flood-bay or reservoir. As the basis of the simulation a HEC-RAS model was applied using the data of the 2006 flood from March 22 until May 31. During the study we assumed, that the reservoir has uniform border (levee) heights. We ran the model for two cases: (1) the levee failure occurs at a stage 1.0 m lower (958±10 cm) than the peak flood, and (2) the levee failure happens at the peak of the flood (1050±10 cm). The results of these simulations were compared.

In the first case the maximum out-flowing discharge would be 1255 m^3/s, whilst in the second case it is 1698 m^3/s. The reservoir (113,7 km^2) would be filled up to 84.5 m asl in the first case, while in the other case just to 84.0 m asl, because in the latest the falling limb of the Tisza could supply less water into the reservoir. Consequently in the first case the reservoir would be filled up in 13 days by 700 million m^3 water, while if the levee failure occurred at the peak-flood only 650 million m^3 water would out-flow to the reservoir in 11 days, and after that would the water would flow back to the Tisza from the reservoir.

The greatest changes in the hydrology of the Tisza occur in the close vicinity of the levee failure, but there are only 1% difference between the two levee failure scenarios. In both cases the greatest stage reduction (1.52-1.54±0.1 m) appears at Mindszent. On the downstream section at Tiszasziget (50 km far from Mindszent) the stage reduction is only 1.18-1.22±0,1 m, whilst on the upstream section at Csongrád (30 km far from Mindszent) it is even smaller (0.84-0.86±0.1 m). On the upstream section the stage reduction effect is lessen by the water supply from further upstream. If the levee breached at a stage 1.0 m lower than the peak of the flood the maximum of the stage reduction would appear 6-7 days after the levee failure, though it would be faster by 1 day in the second case, due to higher initial water out-flow. Yu (2013) also studied levee failures at various water levels applying laboratory experiments, and he found that if a levee failure occurred at higher stage the processes are faster.

In case of levee breach at lower stage, the date of the peak-flood shifted in time, for example the peak of the flood at Mindszent occurred 6 days later and at lower stage by 0.78±0.1 m than the original 2006 flood-wave. Both simulations prove that the water flowing backwards form the reservoir to the Tisza increases the water level of the falling Tisza by maximum 0.74 m. However in this period the accuracy of the model decreases, therefore the dynamics and the effect of the backflow were not examined in detail.

As a result of the levee breach the slope conditions of the Tisza alters significantly by the same degree regarding both simulations. On the upstream section, between Csongrád and Mindszent the slope increases from 4.0 cm/km to 6.5 cm/km while downstream of the levee failure it decreases from 3.5 cm/km to 1.9 cm/km. The degree of the slope change decreases proportionately by distance from the point of the levee failure. The levee breach influences the stream power too. At the first simulation (at 958 cm stage) the stream power increases from 4.0 W/m to 5.5 W/m on the upstream section at Csongrád, while downstream of Mindszent it decreases significantly from 3.5 W/m to 1.5 W/m. In the second case (at 1058 cm stage) the stream power increases from 3.3 W/m to 5.0 W/m on the upstream and decreases from 4.1 W/m to 1.4 W/m on the downstream section. The alteration of slope conditions and the stream power could effect the channel formation. On the upstream sections due to the 50% rise in these values intensive bank erosion and incision could take place, and as the sediment transport could become more intensive, the overbank floodplain aggradation will accelerate. Meanwhile the values on the downstream section halves, so the transportation of the sediment slows down, thus in the channel accumulational processes and intensive mid-channel bar and point-bar formation could be characteristic.

The results of the study could be applied in flood management, since in case of a levee failure or during a controlled levee opening similar hydrological processes could be expected. However, every flood is unique and our model was based on the record high flood of 2006, thus the model should be calibrated and run on another floods, so the results could be generalized.

The construction of the “Szeged Flood Reservoir” is among the plans that would increase the flood safety of the nearby areas of the Tisza, however its planned area (67 km^2) is less by 40% than the reservoir area we used during the simulations. Therefore, it would reduce the flood levels only by 0.4 m (Bódis, 2010), though in our model the flood level decrease would be at least three times greater. In order to verify which plan would be more profitable, the economic value of the reservoir area should be calculated.

The levee failure in 1879 ensued at lower water level (806 cm) by Petres, but the location of the levee failure was only few km far from the simulated location. The flood inundated the same reservoir, but after breaking several secondary levees it flowed further south and destroyed Szeged. During this levee failure the stage of the Tisza was dropped by ca. 1.0 m (Dégen, 1969), which is quite similar to the simulated event, showing the validity of the model. Applying the SWAN program Borza (2008) also simulated the effects of a levee failure based on the data of the 2006 flood, and he found that the discharge of the outflow could be 1300-1400 m^3/s and the water level would be dropped by 1.1 m, which are very similar to our values and it confirms the utility of the HEC-RAS model.

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References

Bezdán, M. 2011. A szabályozott Tisza vízjárása tulajdonságai a Tiszafüred alatti folyószakaszokon. (Hydrology of the Tisza downstream of Tiszafüred) PhD dissertation, SZTE TFGT, Szeged, 120 p. (in Hungarian)

Bódis, K. 2010. Digitális Domborzatmodellek és alkalmazási lehetőségek az árvízi kockázatelemzésben. (DTMs and their application in flood risk management) JATEPress, Szeged, 172 p. (in Hungarian)

Borza, T. 2008. A Sövényházi ártéri öblözet lokalizációs tervének felújítása 2D árvízi elöntés modellezés segítségével. (2D-modelling of the Sövényháza Reservoir) Diplomaterv, BME Vízépítései és Vízgazdálkodási Tanszék, 67 p. (in Hungarian)

Dégen, I. 1969. Vízgazdálkodás I. (Water management) Tankönykiadó Vállalat, Budapest. 220. (in Hungarian)

Haghizadeh, A., Shui, L., Mirzaei, M., Memarian, H. 2012. Incorporation of GIS Based Program into Hydraulic Model for Water Level Modeling on River Basin. *Journal of Water Resource and Protection* 4, 25–31. DOI: 10.4236/jwarp.2012.41004

Hernesz, P., Kiss, T. 2013. A Tisza meder partfalának vizsgálata. (Stratigraphy of the Tisza banks) *Hidrológia Közlöny* 93(2), 13–19. (in Hungarian)

Józsa, J. 2001. Felszíni vizek áramlási és transzport folyamatainak numerikus modellezése. (Numeric modelling of flows) *Hidrológia Közlöny* 81(4), 264–266. (in Hungarian)

Kamanbedast, A., Esfandiar, Y. 2011. Investigation and Study of Morphological Changing of Rivers with Using HEC-Geo-RAS and Mike 11 Software. *World Applied Sciences Journal* 13(5), 1253–1258.

Karatzas, P., Kourgialas, N. 2012. A hydro-economic modelling framework for flood damage estimation and the role of riparian vegetation. *Hydrological Processes* 27, 515–531. DOI: 10.1002/hyp.9256

Kiss, T., Hernesz, P., Sipos, Gy., 2012. Meander cores on the floodplain – the early Holocene development of the low-floodplain along the Lower Tisza Region, Hungary. *Journal of Environmental Geography* 5, 1–10.

Kiss, T., Fiala, K., Sipos Gy. 2008. Altered meander parameters due to river regulation works, Lower Tisza, Hungary. *Geomorphology* 98(1–2), 96–110. DOI:10.1016/j.geomorph.2007.02.027

Knighton, D. 1998. Fluvial Forms and Processes. Routledge, New York, 383p.

Konecsny, K. 2000. Az országhatáron túli tájátalakítás hatása az Alföld vízviszonyaira. (Human impact on rivers) In: Pálfai, I. (ed.): A víz szerepe és jelentősége az Alföldön. Békéscsaba, 27–45. (in Hungarian)

Kovács, S. 2007. Kisköre és a déli országhatár közötti Tisza szakasz lefolyásviszonyainak jellemzése. (Modelling of the flow conditions between Kisköre and the southern border of Hungary) ATIKÖVIZIG and KÖTIKÖVIZIG, Manuscript, 1–43. (in Hungarian)

Lászlóffy, W. 1982. A Tisza. Akadémia Kiadó, Budapest, 610 p. (in Hungarian)

Pregun, Cs. 2009. Felszíni vízfolyások digitális hidrológiai modellezésének alkalmazása a vízminősítésben. (Digital hydrological modelling of surface waters) *Hidrológia Közlöny* 89(1), 9–21. (in Hungarian)

Rakonczai, J., Kozák, P. 2009. Az Alsó-Tisza-vidék és a Tisza. (The Lower Tisza region and the Tisza) *Földrajzi Közlemények* 133(4), 385-395. (in Hungarian)

Sándor, A. 2011. A hullámtér-feltöltődés folyamatának vizsgálata a Tisza középső és alsó szakaszán. (Floodplain aggradation along the Lower and Middle Tisza) PhD dissertation, SZTE TFGT, 120. (in Hungarian)

Schweitzer, F. 2003. Folyóink hullámtereinek fejlődése, kapcsolatuk az árvizekkel és az árvízvédelmi töltésekkel (Floodplain development and floods) in: Teplán I. (ed): A Tisza és vízrendszere. MTA TTK, Budapest, 107–117. (in Hungarian)

Starosolszky, Ö. 1996. Gondolatok a hidraulikai modellezésről. (Introduction to hydraulic modelling) *Vízügyi Közlemények* 78(2), 166–171. (in Hungarian)

Szigyártó Z., Rátky I. 2010. Eljárás a Vásárhelyi terv továbbfejlesztése során előirányzott árvízi tározórendszer hidrológiai méretezéséhez. (Handbook for planning flood-storage reservoirs) *Hidrológiai Közlöny* 90(2), 25–35. (in Hungarian)

Szigyártó, Z. 2012. A Kiskörei-tározó hatása az árhullámok ellapulásra. (The effect of the Kisköre Storage Lake on floods) *Hidrológiai Közlöny* 92(2), 25–31. (in Hungarian)

U. S. Army Crop of Enginners. 2010. Users's Manual of HEC-RAS River Analysis system 4.1.

Vágás, I. 2003. Az 1998. novemberi árhullám hidrológiai értékelése a Tisza-völgyi árvizek sorában. (Hydrology of the 1998 flood) In: Szlávik, L. (ed.): Az 1998. évi árvíz. Vízügyi Közlemények különszám 1, 85–91. (in Hungarian)

Whisler, F.D. Watson K. K. 1968. One-dimensional gravity drainage of uniform columns of porous materials. *Journal of Hydrology* 6, 277–296. DOI:10.1016/0022-1694(68)90104-2

Yalcin. G., Akyurek, Z. 2004. Analysing Flood Vulnerable Areas with Multicriteria Evaluation. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences* 35(2), 359–364.

Yu, M. 2013. Investigation of non-cohesive levee breach by overtopping flow. *Journal of Hydrodynamics* 25(4), 572–579. DOI:10.1016/S1001-6058(11)60398-4

References from the internet

[1] http://www.evizig.hu/Vasarhelyi/Vasarhelyi.asp
[2] http://www.mikepoweredbydhi.com/products/