MŰEGYETEM 1782

Edina Balogh

Risk-based analysis of emergency flood reservoirs

Theses of the PhD dissertation

Supervisor: **Dr. László Koncsos**

Budapest University of Technology and Economics
Faculty of Civil Engineering
Department of Sanitary and Environmental Engineering

2012

1. Introduction

Development of the human civilization is accompanied with extreme events of river regime and coastal floods. In consequence of the technical and economic development, accomodation to floods was changed into controlling behaviour more and more. Delicate balance of this symbiosis was split.

Inhabiting flood areas and using them as cultivation area people became more vulnerable. The meaning of “flood” became increasingly “catastrophe” than a phenomenon of nature which can be used for our own aims. Altough there is a good progress in flood protection, approximately 10 % of people are threated by floods even now (Szlávik, 2002). Humanity has to face a significant increase in losses caused by extreme hydrological events, like floods. There is a growing tendency in flood danger and in the number of serious flood events worldwide. Floods cause thousends of fatalities and tens of billions of US dollars per year (Kundzewicz et al, 2001). The reason of this phenomenon is very complex. Basically the disadvantageous changes can be explained with three reasons. These are the direct human intervention, the effects of climate change and the economic development of the areas endangered by floods.

The geographical conditions of Hungary are rather disadvantageous from the point of view of flood risks. The country lies at the lowest part of the Carpathian basin. The area which is at risk of floods is 21248 km^2. This is the greatest proportion in Europe (Szlávik, 2003). The whole flood area crumbles into 151 flood basins, which are protected with a 4200 km long levee system. The watershed of the Tisza River is quite important: 50% of the whole area of Hungary belongs to it (Vágás, 1982). That area involves 96 flood basins (15600 km^2), which are 73% of the whole flood area in Hungary (Szlávik, 2003). In Hungary we can see a continuous increase in flood levels and in frequency of floods, like all over the world.

That demands further development in flood control both in theory and in practice. To control the floods threaten us year by year, it needs to develop new strategies which combine the existing flood control system with novel elements and so can suit the requirement of flood safety and demands come up nowadays (like nature reserve, ecological demands) in the future.

In Hungary a new conception called *Vásárhelyi Plan* was developed after the serious floods on the Tisza River around 2000, which caused severe losses. The main element of that conception is the emergency flood reservoir system, which can provide the provisional storage of water which cannot be conveyed on a safety way during serious flood events (Government of the Hungarian Republic, 2003).

There is a need for change in definition of flood safety as well. It is necessary to change the foregoing deterministic approach into probabilistic approach, and the development and evaluation of flood control strategies must be laid at basis of risk analysis (UN-ECE, 2000; Nagy, 2005). The principles of the risk-based approach were already drafted in the document "*Best Practices on Flood prevention, Protection and Mitigation*" at EU-level (EC, 2003). The Communication from the Commission (EC, 2004) and the Directive 2007/60/ec of 23 October 2007 on the flood risks (EC, 2007) built the frame of the assessment and management of flood risk for the EU countries. These documents determined concrete requirements and deadlines concerning the elaborating of flood hazard maps, flood risk maps and flood risk management plans.

2. Aim of the research

The purpose of the dissertation was to determine the optimal release policy into emergency reservoirs along a river protected with levee reaches. The decision on the timing and magnitude of release into emergency reservoirs along levee-protected rivers is influenced by several key factors, including

- the observed or forecasted upstream hydrograph,
- the location and size of the reservoirs,
- the observed or forecasted upstream hydrograph,
- the uncertain protection capacities of the levee reaches involved,
- magnitude of flood losses in case of possible levee failure(s),
- effect of possible levee failure(s) on upstream and downstream flood levels.

The aim was to develop a methodology which consider these factors and provide a release policy applicable to a given flood situation. The object of the analysis was to develop theoretical relations, determine a theoretically possible release policy and the measurement of the reachable effects.

Involving risk in the definition of the reservoir effect, I determined the release policy which results in the maximum decrease in flood risk. Determination of flood risk was based on inundation losses and failure probabilities. It was an aim to adapt novel Hungarian loss functions and levee performance functions to the target.

Furter aim was to present the risk-based method on a pilot area. As a pilot area a part of the Hungarian Middle-Tisza was chosen, where more emergency reservoir are planned to build in the frame of the *Vásárhelyi Plan*. The results were compared with the output of a water level-based analysis, which was applied more common in Hungary up to now. In the water level-based investigation the release policy results in the highest decrease in the water levels was determined. Another aim was to examine another (non-optimal) release policy and compare the efficiency of the reservoirs in the two different cases.

3. Methodology

To achieve the proposed object of the analysis it needed to develop a complex methodology. Besides applying the existing hydrological and hydraulic modelling tools, it needed to build up new methods too. Main elements of the developed methodology are summarized in **Figure 1**.

In the focus of the methodology there is an optimization problem. The role of the optimization is to determine the reservoir withdrawal time series which results in the maximum effect of emergency reservoirs. The methodology is framed by an unsteady 1D hydrodynamic model, which calculates the downstream water levels as the initial parameters of the analysis. The applied 1D model is based on the solution of the Saint-Venant equations of mass and momentum conservation (see e.g. Abbott, 1979). The equations are solved with the Preissmann implicit scheme, applying the so-called double-sweep method (Liggett and Cunge, 1975).

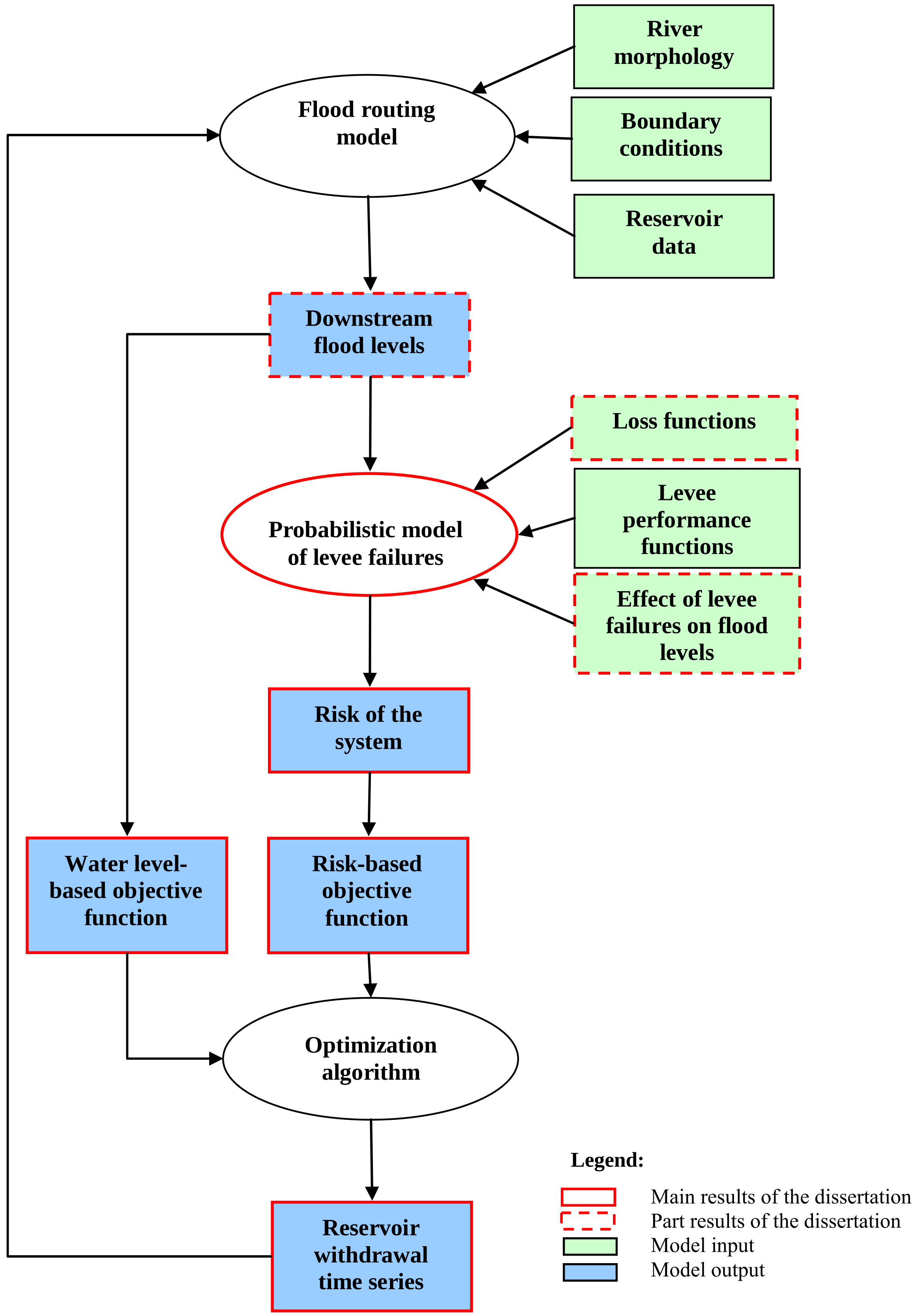

Figure 1: Main elements of the methodology

The optimization problem is solved applying two different objective functions, according to the two different definitions of the reservoir effect.

- The water level-based objective function measures the decreasing effect of reservoirs on the flood water levels. It summarizes the decrease in the flood water levels caused by the reservoirs in each section along the whole river reach. The decrease values are weighted according to the distance from the neighbouring sections.
- The risk-based objective function measures the decreasing effect of reservoirs on flood risk. To define the risk-based objective function determination of levee failure probabilities and expected inundation losses was needed. To determine levee failure probabilities it needed to take effects of possible levee failures into consideration. Therefore a probabilistic model of levee failures was developed. The objective function could be determined according to the probabilistic model of levee failures and the loss functions.

As optimization algorythm an adaptive Monte-Carlo method was applied (Koncsos et al, 1995; Koncsos, 2008). The decision variable was the amount of daily reservoir withdrawals (q_t, where t is the serial number of time interval) changing between zero (when there is no withdrawal) and the maximum sluice capacity of the reservoir. For each reservoir the maximum capacity of the reservoir was a limiting condition, it could not be exceeded by the total release to the reservoir.

The methodology was applied to an example flood. It retained the main characteristics of the historical 2000 year event but with a slightly smaller probability of occurrence, what means higher flood levels. The applied mathematical statistical process was based on the so-called Peak Over Threshold method (see e.g. Zsuffa, 1997).

4. Summary of the results

In the present dissertation the operation of emergency flood reservoirs along a river protected with levee reaches was analyzed. The aim was to determine the release policy which results in the maximum decrease in flood risk, involving risk in the definition of the reservoir effect. To define the risk-based objective function, I had to achieve methodological developments. These results are summarized in **Thesis 1** and **Thesis 2**.

<u>Thesis 1</u> [14]:

I determined that in case of risk-based analysis of flood control system consists of more reaches of levee the value of *inundation losses x failure probability* over-estimates the risk. In such a system during the simulation of a flood wave only the failure probability is determined in the function of the flood levels, there is no decision on occurring of levee failure. So it is impossible to take effects of a possible levee failure into account directly. These effects on the other levee reaches can be decrease in actual value of failure probability and inundation losses as a function of water levels. To eliminate this problem I developed a probabilistic model of levee failures which can consider the decreasing effect on water levels of possible levee failures as well. The model can be applied to levee systems consisting of n **reaches. In case of** n **levee reaches, the number of the failure combinations which compose the whole event space is** 2^n**. The summarized probability of all failure combinations of a system consisting of** n **reaches is:**

$$P = \sum_{m=1}^{n} P_m$$

where m **is the number of reaches on which there is a failure in the actual failure combination.**

$$P_m = \sum_{\substack{j1=1 \\ j2=j1+1 \\ \dots \\ jm=j(m-1)+1}}^{\substack{n-m \\ n-m+1 \\ \dots \\ n}} \left\{ \prod_{h=1}^{m} P_{jh}\left(h_{jh} - \sum_{\substack{t=1 \\ t\neq h}}^{m} m_{jh}^{jt} \right) \cdot \prod_{\substack{i=1 \\ i\neq j1,\dots,jm}}^{n} \left[1 - P_i\left(h_i - \sum_{t=1}^{m} m_i^{jt} \right) \right] \right\}$$

where $m_{jh}^{jt} = 0$ **if** $jh < jt$ **and** $m_i^{jt} = 0$ **if** $i < jt$.

<u>Thesis 2</u> [14]:

To determine the optimal release policy into emergency flood reservoirs I developed a risk-based objective function. It basis on the probabilistic model of levee failures and it handles the possible

inundation losses in the same system. The total risk of the system can be defined as the sum of the risks which belong to each failure combination. The general formula for *n* levee section is:

$$R = \sum_{m=0}^{n} R_m$$

where *m* is the number of reaches on which there is a failure in the actual failure combination.

$$R_m = \sum_{\substack{jm=j(m-1)+1\\ \dots\\ j2=j1+1\\ j1=1}}^{\substack{n-m\\ n-m+1\\ \dots\\ n}} \left\{ \prod_{h=1}^{m} P_{jh}\left(h_{jh} - \sum_{\substack{t=1\\ t\neq h}}^{m} m_{jh}^{jt}\right) \cdot \prod_{\substack{i=1\\ i\neq j1,\dots,jm}}^{n}\left[1 - P_i\left(h_i - \sum_{t=1}^{m} m_i^{jt}\right)\right] \cdot \sum_{l=1}^{m} L_{jl}\left(h_{jl} - \sum_{\substack{k=1\\ k\neq l}}^{m} m_{jl}^{jk}\right)\right\}$$

where $m_{jh}^{jt} = 0$ **if** $jh < jt$ **and** $m_i^{jt} = 0$ **if** $i < jt$

The risk-based objective function was defined as the value of the total risk of the system, which is changing as the function of the release policy into the reservoir(s).

Development of the probabilistic model of levee failures and the risk-based objective function made it possible to elaborate a general method for risk-based optimization of the release policy into emergency reservoirs. The steps of the process are the following:

1. Simulation of levee failures and determination of the decreasing effects on water levels in advance;
2. Determination of probability distribution functions of levee strength for each levee reaches;
3. Determination of inundation loss functions for each levee reaches;
4. Definition of the risk-based objective function;
5. Definition of the limiting condition of the optimization;
6. Execution of the optimization applying an optimization algorithm framed by a 1D hydrodynamic model which is calibrated and validated for the examined river reach:

a) Determination of the flood levels without reservoirs, applying the 1D model. The upper boundary condition is the flow hydrograph of the arriving flood wave;
b) Calculation of the modified flood levels for each levee reaches in case of each failure combination, considering the decreasing effects on water levels of levee failures ;
c) Determination of the failure probabilities and the inundation losses as a function of the modified flood levels for each levee reaches in case of each failure combination, based on the probability distribution functions of levee strength and the loss functions;
d) Calculation of the risk of the system without reservoirs (R^0) as sum of the risks which belong to each failure combinations;
e) Initial value of the objective function is: $H^{opt} = R^0$;
f) Determination of the flood levels, considering the reservoirs as outflow, proceeding from the actual values of the optimization parameters (in the first optimization step these are the initial values, in the further steps the values renewed by the algorithm), considering the limiting condition;
g) Calculation of the modified flood levels for each levee reaches in case of each failure combination, considering the decreasing effects on water levels of levee failures ;
h) Determination of the failure probabilities and the inundation losses as a function of the modified flood levels for each levee reaches in case of each failure combination, based on the probability distribution functions of levee strength and the loss functions;
i) Calculation of the risk of the system modified by reservoirs (R^T) as sum of the risks which belong the each failure combinations;
j) Actual value of the objective function is: $H^a = R^T$;
k) Examination of the actual value of the objective function:
   if $H^a < H^{opt}$ then $H^{opt} = H^a$ and memorizing of the optimal parameters;
l) Examination of the shut-down condition:
   - if it is not fulfilled, then back to the point f);
   - if it is fulfilled, then the optimization is ended;

7. Optimal values of parameters appoint the release policy into reservoirs which results in the maximum decreasing effect on risk.
8. The value of H^{opt} which belongs to the optimal parameters is the maximum decreasing effect on risk which can be reach using the reservoirs.

These results are summarized in **Thesis 3.**

Thesis 3 [14]:
I developed a method for risk-based determination of optimal release policy into emergency reservoirs along a river protected with levee reaches. In the system consists of levee reaches and reservoirs the release policy into reservoirs which results in the lowest risk is determined applying an optimization algorithm framed with a 1D hydrodynamic model in case of a given flood wave. The value of the risk-based objective function of the optimization can be determined based on the probability distribution functions of levee strength and the loss functions of each levee reaches, considering all of the failure combinations. The value of the objective function is a function of the flood levels, which can be calculated applying the hydrodynamic model.
Decreasing effects of levee failures on water levels are determined by simulations in advance for all failure combinations. The effect of reservoirs on water levels is handled with the hydrodynamic model in every optimization step according to the actual release policy.

Applying the developed risk-based method, I analysed the operation of emergency reservoirs on the Middle-Tisza. I compared the results of that analysis to the output of a water level-based optimization, which is used more common in practice in Hungary. In that method a release policy which resulted in the highest decreasing in water levels is determined. Furthermore I compare the efficiency of the reservoirs applying the optimal release policy to the effectiveness of them applying another (non-optimal) strategy. Conclusions are summarized in **Thesis 4**.

Thesis 4 [2], [4], [5], [13], [14]:
As a consequence of the optimization analysis achieved applying the risk-based and the water level-based objective functions I determined that the optimal release policy into reservoirs on the Hungarian Middle-Tisza demands a considerable lead time preceding the flood peak. The optimal release policy concentrates on the rising phase of flood waves. If the release begins at the moment of the peaking, the decreasing effect on risk or on water level falls considerably. In case of

a given forecasted flood wave I suggest to determine the optimal lead time of release into the reservoirs and to apply a release policy which is as similar as possible to the optimal one, taking the possibilities of the lead time of the flood forecast into consideration.

5. References

Abbott, M. B. (1979): Computational hydraulics – elements of the theory of free surface flows, Pitman, London, UK.

EC (2003): *Best Practices of Flood prevention, Protection and Mitigation.* EC Water Directors Meeting, Athens, Greece, 06.2003.

EC (2004): Commission of the European Communities: Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Flood risk management, Flood prevention, protection and mitigation, COM(2004)472 final. *Official Journal of the European Communities,* 12.07.2004.

EC (2007): Directive 2007/60/ec of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. *Official Journal of the European Communities,* 06.11.2007.

Government of the Hungarian Republic (2003): 1022/2003. (III. 27.) Government regulation (*in Hungarian*). Hungarian Gazette, 2003/30.

Koncsos, L., Schütz, E. and Windau, U. (1995): Application of a comprehensive decision support system for the water quality management of the River Ruhr, Germany. *Modelling and Management of Sustainable Basin-scale Water Resource Systems* (Proceedings of a Boulder Symposium, 07.1995). IAHS Publ. No 231. pp. 97-106.

Koncsos, L. (2008): Decision supporting systems in water quality and flood control planning (*in Hungarian*). *Habilitation thesis.* Manuscript. Budapest.

Kundzewicz, Z. W., Budhakooncharoen, S., Bronstert, A., Hoff, H., Lettenmaier, D., Menzel, L. and Schulze, R. (2001): *Floods and droughts: Coping with variability and climate change.* Thematic background paper. International Conference on Freshwater, Bonn.

Liggett, J.A. and Cunge, J.A. (1975): Numerical methods for the solution of the unsteady flow equations. In: Mahmood and Yevjevich (eds*): Unsteady Flow in Open Channels*, pp. 89–182. Water Resources Publications, Fort Collins, CO, USA.

Nagy, L. (2005): Flood risk according to the failure of levee system. *Ph.D. thesis* (*in Hungarian*). Budapest.

Szlávik, L. (2002): Flood control (*in Hungarian*). In: Somlyódy, L. (ed.): *Strategic issues of the Hungarian water management,* pp. 205-243. MTA, Budapest.

Szlávik, L. (2003): *Analysis of flood safety (in Hungarian).* MTA National Strategic Programme. VITUKI, Budapest.

UN-ECE – United Nations Economic Comission for Europe (2000): Sustainable Flood Prevention. Meeting of the parties to the convention on the protection and use of transboundary watercourses and international lakes. Hague, Netherlands, 23-25. 03. 2000.

Vágás, I. (1982): *Floods of the Tisza River (in Hungarian).* Institute of Water Management Documentation and Education, Budapest.

Zsuffa, I. (1997): *Engineering Hydrology Part 2.* (*in Hungarian).* Műegyetem Publ., Budapest.

6. Publications (2003-2012)

[1] **Balogh, E.** (2003): Economic effects of flood risks on the Upper Tisza River (*in Hungarian*). *Vízügyi Közlemények* 85:(3) pp. 417-432.

[2] **Balogh, E.**, Koncsos, L. (2005): Optimum operation of emergency reservoirs (*in Hungarian*). In: Barna, Zs., Józsa, Zs. (ed.) *PhD researches at Faculty of Civil Engineering*, *BME*. Budapest, 2nd March, 2005. pp. 206-213.

[3] **Balogh, E.** (2005): Economic effects of flood risks on the Tisza River between Tiszabecs and Tokaj (*in Hungarian*). *Hidrológiai Közlöny* 85:(2) pp. 9-16.

[4] Koncsos, L., **Balogh, E.** (2006): Optimum operation of reservoirs (*in Hungarian*). *Hidrológiai Közlöny* 86:(4) pp. 3-6.

[5] Koncsos, L., **Balogh, E.** (2006): Optimum operation of flood control reservoirs. In: Simkova, T. (szerk.) *Flood Protection Conference*. Podbanské, Slovakia, 4-7 December, 2006. pp. 202-211.

[6] Koncsos, L., **Balogh, E.** (2007): Flood damage calculation supported by inundation model in the Tisza valley (*in Hungarian*). *Hidrológiai Közlöny* 87:(5) pp. 23-28.

[7] Koncsos, L., **Balogh, E.** (2007): Flood damage calculation supported by inundation model in the Tisza valley. In: Di Silvio, G., Lanzoni, S. (ed.) *32nd IAHR Congress: Harmonizing the Demands of Art and Nature in Hydraulics.* Venice, Italy, 1-6 July, CD-Paper SS05-12-O. p. 10.

[8] Koncsos, L., **Balogh, E.** (2007): Interaction of climate change and flood control measures (*in Hungarian*). *Conference on Climate change – Economic climate change.* Budapest, 4th October, 2007.

[9] Koncsos, L., **Balogh, E.** (2008): Flood disaster mitigation by inundation of the deep floodplain. In: Simonovic, S.P., Bourget, P.G., Blanchard, S.F. (ed.) *4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability.* Toronto, Canada, 6-8 May, 2008. CD-Paper 86. p.8.

[10] **Balogh, E.** (2009): Excess water in Hungary – State of the art (*in Hungarian*). *Hidrológiai Közlöny* 89:(4) pp. 53-55.

[11] Koncsos, L., **Balogh, E.** (2009): Dynamic modelling of flow control aiding sustainable land management in Bodrogköz. *Thaiszia - Journal of Botany* 19:(Suppl. 1) pp. 527-542.

[12] Koncsos, L., **Balogh, E.** (2009): Risk of excess water calculating by up-to-date hydroinformatical assets (*in Hungarian*). *27th National Meeting of the Hungarian Hydrological Society*, Baja, 1-3 July, 2009. CD p. 9.

[13] Koncsos, L., **Balogh, E.** (2010): A simulation-optimisation methodology for designing the operation of emergency reservoirs in the Hungarian Tisza basin. *Periodica Polytechnica - Civil Engineering* 54: (2) pp.101-106.

[14] **Balogh, E.**, Bogárdi, I., Koncsos, L. (2012): Optimum release policy of emergency reservoirs (*in Hungarian*). *Hidrológiai Közlöny*, 92:(1) pp. 41-47.

Edina Balogh
Tel: +3670 2445775
Fax: +3676 411159
E-mail: eabalogh@gmail.com