THESES OF PH.D DISSERTATION

Digital elevation models and their applications in flood risk management

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1. Introduction

Research into the hydrological applications of digital elevation models has recently become very significant, when numerous national and international projects are aiming for sustainable water-resource management, modelling and forecasting the increasingly frequently occurring environmental phenomena driven by extreme hydrological processes and the estimation and mitigation of their damages if possible.

Modelling relief, as one of the most determinant elements of landscape components (Mezősi and Bódis 1999) has become essential in environmental research (Moore et al. 1991; Goodchild et al. (Eds.) 1996; Burrough and McDonnell 1998; Longley et al. (Eds.) 1999, Wilson and Gallant (Eds.) 2000; Tóth et al. 2004; Hengl and Reuter (Eds.) 2007; Maune (Ed.) 2007; Peckham and Jordan (Eds.) 2007). Escalating hydrological problems (extreme events, floods, droughts, managing water-resources, soil erosion, environmental effects of climate change) and the development of mathematical modelling techniques involving digital (spatial) data processing and analyses, GIS (geographical information systems) and RS (remote sensing) technologies have also opened up new prospects to hydrological modelling (Beven and Moore (Eds.) 1995; Bates and Lane (Eds.) 2000; Grayson and Blöschl (Eds.) 2000; Beven 2001). These developments have enabled the spatial discretisation of hydrological processes, and the resulting models are called distributed models. The principle of distributed modelling is that the analysis of sub-processes is done by dividing the area under investigation into elements (cells, grids), within which the processes are represented. Among the most important components, there are the terrain and its derivatives. Thus cell-based digital elevation modelling and applications in hydrological modelling is targetted by several research activities; however the Hungarian literature for the topic is considered to be quite limited.

2. Objectives

My work has two main goals: the first is describing digital elevation models and modelling tasks generally, but more comprehensively and in greater detail than one can learn from the available Hungarian textbooks. The second objective is to present the applicability of elevation models and derived spatial information using GIS operations in hydrological modelling for decision support, addressing the theoretical support of strategic and operative flood prevention, making the presented modelling technique an integral part of flood risk management.

My intention has been to summarize and systematize the information of relevant references augmented by my own practical experiences covering all the phases of data processing. My research results are presented by three case-studies carried out in the Tisza Basin. Two main methodological approaches were demonstrated. Firstly digital elevation model (DEM) applications and thus the significant role of applied geoinformatics in decision support for preliminary flood protection plans (e.g. reservoir management, inundation extent and damage estimation). Secondly, in further hydrological and hydraulic modelling aiming impact assessment of new flood-control works (optimisation problems of reservoir-management, flood risk mapping).As a practical application of research experiences I have also presented a methodology for producing static topographic input layers containing parameters of surface and riverbed geometry for a distributed hydrological (rainfall-runoff) model developed to simulate floods in large, continental scale river basins.

One of the goals of my dissertation is to present the theoretical background and the practical applicability of the developed and described modern methodology that combines the results of hydrologic-hydraulic modelling, geographic-topographic suitability and economical-social properties. This methodology could also provide a valuable environment for catchment-based or continental preliminary flood risk estimation, flood hazard and flood risk mapping at either national or regional scale, and could thus be a tool for the preparation and communication of flood risk management plans.

3. Applied techniques

The fundamental component to accomplish the research objectives is the digital elevation model, which has been defined by many authors in many different ways. Probably the simplest definition is that the DEM is "any digital representation of the continuous variation of relief over space" (Burrough 1986; Moore et al. 1991), or more briefly "any digital representation of the terrain" (Goodchild and Kemp (Eds.) 1990). Based on one of the most widespread definitions, the Digital Elevation Model (DEM) is a representation of the Earth's surface (or subset) excluding natural or artificial features (e. g. Burrough 1986; Kertész 1991; Hutchinson and Gallant 1999; Jordán 2007). When the digital elevation model is enhanced by different terrain elements (vegetation, building) and also includes their elevation attributes, the name of the model is Digital Terrain Model (DTM).

4. Results

The dissertation gives an overview of the definition of digital elevation models and their various, usually application- and content-dependent namings, as well as summarising the methodologies of their generation or sources (including publicly available, global data-sources) and describes the properties of DEM quality assessment. The dissertation also reviews the geoinformatic operations that must be performed on practically every DEM dataset before the investigation of any geographic phenomena. Among these preparatory steps are the definition of a proper projection and coordinate system or appropriately executed coordinate transformations ensuring the correct geographic extent of the model (Bódis 1999). In addition most applications also require the calculation of DEM-based terrain parameters (gradient, slope exposure, flow network, etc.).

Summarising the different sources and types of digital elevation models beyond the technical details, I have endeavoured to reveal the advantageous and disadvantageous characteristics of different models focusing on the requirements set by possible further environmental-hydrological applications. The geoinformatic operations were accomplished and the spatial distributions of derived surface parameters were demonstrated using the digital elevation model of the Velence Mountains (Hungary). The model was created (digitised, transformed, interpolated) using all the elevation information contained in paper-based topographic maps of the area (Bódis 1999; Bódis and Csuták 2001).

Specific modelling tasks require various preparatory procedures, modelling techniques and analysis methods. The dissertation presents the research results from four case-studies based on different data-sources describing the digital elevation modelling and analysing techniques, that were developed and established, completed operations, the intermediate results as well as their applications and further processing possibilities.

4.1 Application of DEM-based derived information in optimising flood mitigation effect of reservoirs

a) In the case of the planned flood retention reservoirs in the Upper-Tisza Basin (Carpathian Mountains, Ukraine, 42 new reservoirs, total capacity ca. 300 million m^3) a geoinformatic system including a geo-database of reservoirs was developed based on elevation models and the derived flow network. This sophisticated geo-database is suitable for providing essential spatial data input for further hydrological modelling, planning and decision making (Szabó, Bódis, Tóth, Jakus 2008).

b) Based on the methodology I developed and presented in the study, I defined geometrical parameters of the planned reservoirs. Although these were not detailed in the available documentation (e.g. capacity curves, Figure 1, phases of filling, Figure 2); nevertheless they are still fundamental in simulation-based hydrological analyses and impact assessment of the reservoir-system (Szabó, Bódis, Tóth, Jakus 2008).

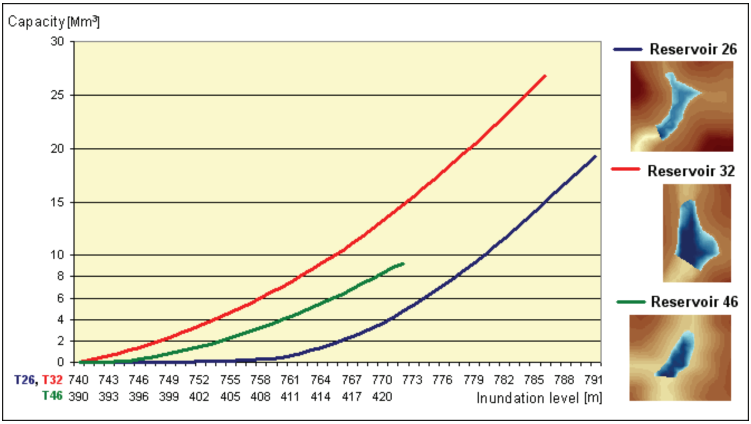

Fig. 1. Storage capacity curves in the case of three flood retention reservoirs

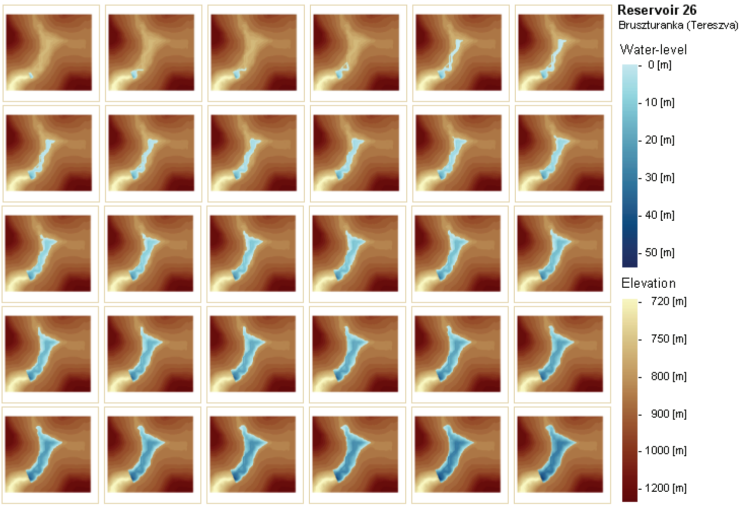

Fig. 2. Phases of filling in the case of the reservoir on the Bruszturanka river (ID26)

c) The established and presented methodology and model was successfully applied in solving optimisation problems of reservoir-management including an optimized strategy of releasing the reservoirs, minimising storage time while the released water was kept within previously given water level and discharge limits, Figure 3) (Szabó and Bódis 2006).

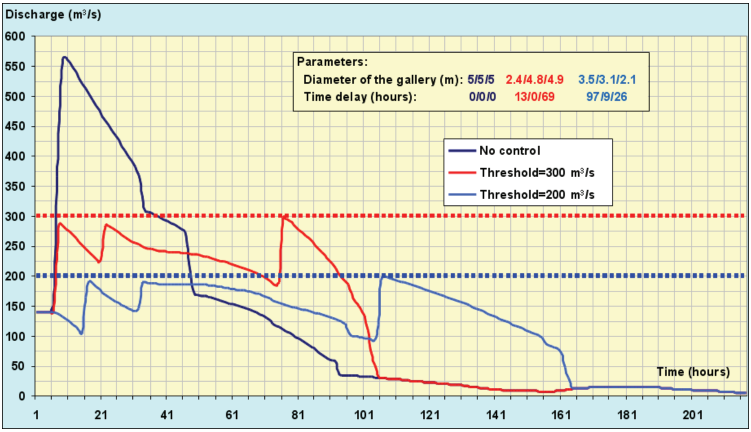

Fig. 3. Optimal reservoir releasing strategy (allowed discharge, suggested timing and diameter of galleries in the case of three reservoirs)

d) The first impact assessment study of the planned reservoir-system was carried out using results from a statistical evaluation of time series, while catchment-responses to spatially distributed probable maximum precipitation have been simulated based on the condition if the reservoirs were implemented already in the basin (Szabó, Bódis, Tóth, Jakus 2008).

e) The results of the completed simulations do not show the expected efficiency of the installation of flow-through type flood retention reservoirs in mitigating flood waves (the simulations demonstrated about 8 % decrease in flood peak discharge); however the complex effects of the reservoir system and the additionally planned flood retention polders with regulated outflow in the flatland still has to be done (Szabó, Bódis, Tóth, Jakus 2008).

4.2 High-resolution digital elevation models for design of flood emergency reservoirs

a) A combined, high-resolution digital elevation and terrain model of a planned reservoir (Szeged) was created for testing whether the volumetric values published in the multistage and multi-versioned public documentation of the New Vásárhelyi Plan were actually realistic (Bódis, Szatmári, Szakál, Vízhányó 2003).

b) Based on model calculations it can be concluded that the planned numbers presented in the public conceptual plans were defined roughly using a non-published procedure and that there are inconsistencies between the planned and the modelled values (Figure 4) (Bódis 2007).

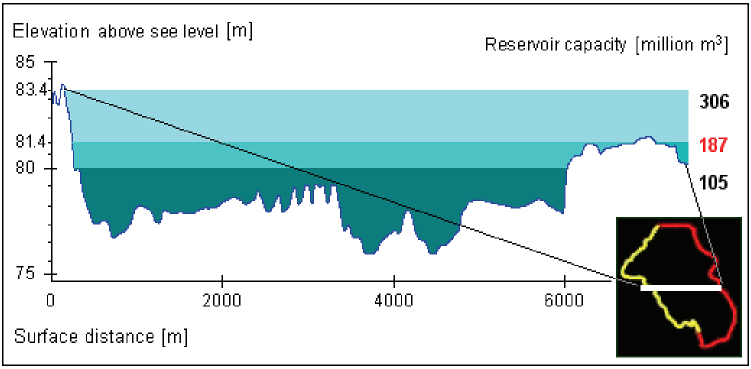

Fig. 4. The estimated required inundation levels of different volumetric capacities. The published 187 Mm^3 capacity can be reached only by a minimum 81.4 m inundation. The white line in the inset at the lower right corner shows the location of the presented profile

c) As a result of elevation modelling, it was suggested that the published estimated quantities of releasing of the reservoir (volumetric data and timing) should be redesigned.

d) By applying the presented methodology, the storage capacity of the selected topographical surfaces can be calculated within a reasonable timeframe. The input data can be enhanced and modified by any relevant further spatial information and the storage capacity can be estimated according to the modified circumstances. The flexibility and adaptability of the method make it indispensable in decision support for the planning of similar projects (Bódis 2007).

e) The digital elevation model created for the study and the results of the geoinformatic analyses (Bódis 2007) contributed to the revision and modification of design parameters in the published documentations and thus to the technical preparation of the New Vásárhelyi Plan.

4.3 Elevation model applications in flood risk mapping

a) According to the frequently used function in the quantitative risk assessment:
'risk of an event' = 'probability of the occurrence' × *'consequences'.*
In the case of flood risk assessment, the 'probability' component can be estimated by frequency analysis of historical discharge data records. The 'consequences' can be approximately calculated by damage functions combining the economic value of the flooded area with the inundation water depth in the fields. A methodology of mapping the components of flood risk is described in the dissertation (Szabó and Bódis 2006).

b) Based on hydraulic modelling and time-series analysis, and supposing that there is no further defensive operation performed along the river, the location of dike-overtopping can be determined. The modelling also provides the duration and discharge parameters of flood events characterised by different probabilities (Szabó and Bódis 2006).

c) In order to demonstrate the suitability of the developed theoretical methodology I have created a hypothetical localization plan of flooded water taking into account the terrain parameters. The localizing blocks and lines are auxiliary objects in order to describe and visualize the methodology; apart from the planned reservoir north of Szeged they are not necessarily included in real defence plans. The presented methodology can be further refined by any additional information suggested by experts of flood protection modifying the given circumstances (Bódis 2006).

d) I have mapped the flood extent and localization of flooded zones belonging to different probabilities (Figure 5) using topographic information and the modelled embankments (Bódis 2006).

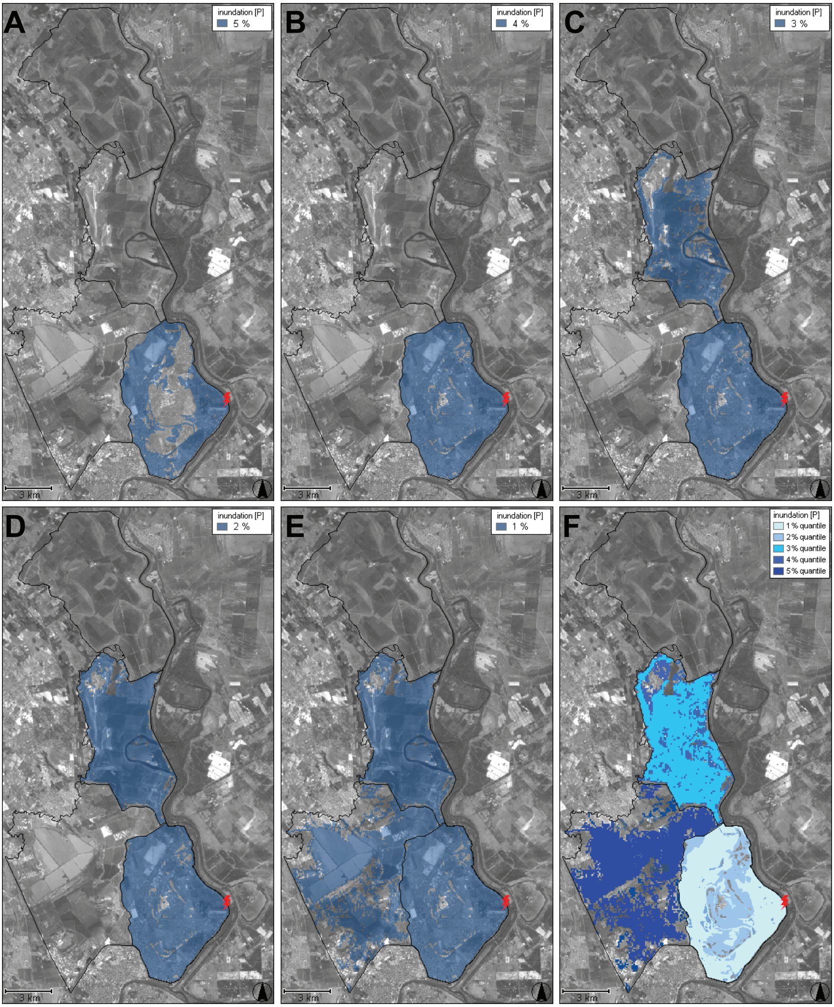

Fig. 5. Maps of localization of flooded zones belonging to different probabilities based on elevation and modelled embankments. In the first phase of mapping the block closest to the estimated dike-overtopping (red mark) was filled. This block was sufficient to store the total volume of the flooded water characterized by 5 and 4 % probability (22 and 58 Mm^3) in the spatial distribution shown in Figures A and B. In the case of floods characterised by lower probability but larger discharge the neighbouring blocks are also inundated (Figures C, D, E). Figure F shows the storage of water bodies with given probabilities

e) I have calculated flood water depth (Figure 6) and overlaid the geoinformatic layer of flooded zones (water depth) with land use categories (Figure 7) in order to estimate the flood damages and define the relative damage function.

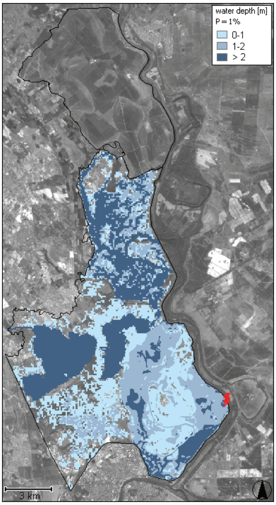

Fig. 6. Water depth

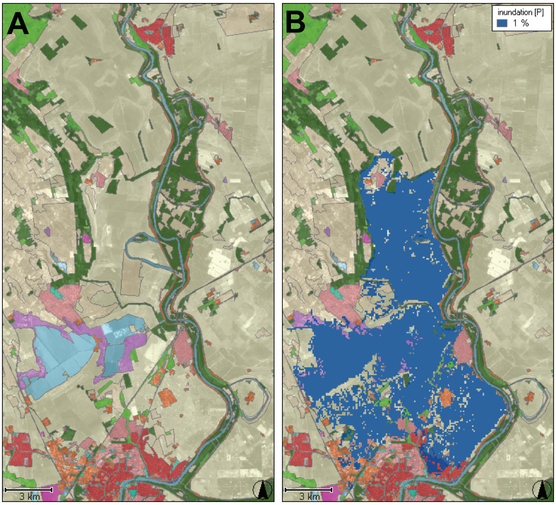

Fig. 7. Land use (A) and flooded zone (B)

f) The CORINE 2000 database was used in the case study as it is a frequent input in similar mapping tasks. The general characteristics of thematic content of the database highlighted that a properly detailed and up-to-date land cover and land use database is necessary for setting up a suitable damage function. For appropriate damage estimation a more detailed database or at least a GIS inventory of the most valuable objects to be protected with high priority is required. The applied land cover database showed ‘non-irrigated arable land’ in the area where industrial installations of the Algyő oil and gas field are located (Bódis 2006). The potential damage cannot be estimated on the level of arable lands in this case.

g) Based on the CORINE database, as well as visual interpretation of higher resolution aerial images, the land cover type of the emergency reservoir closest to the study area (Szeged) is also ‘non-irrigated arable land’. This area would be covered by more than 3-meter-deep water. Using the damage factors of the most frequently applied damage estimation method (Multi Coloured Manual, MCM) the estimated damage would be equal to the maximal damage, independently of the duration of inundation.

4.4 Application of elevation model in continental scale hydrological models

a) I performed and presented geoinformatic operations on global digital elevation models to produce static topographic input layers for a hydrological (rainfall-runoff) model to be developed to simulate floods in large, continental scale river basins.

b) The study gave the opportunity for the comparison of elevation data and derived parameters based on two public data sources (GTOPO30 and SRTM). The dissimilarities between the two datasets from different sources and resolutions are significant from the point of view of hydrological modelling, not only because of their numerical difference, but they are also quite remarkable in their differences when comparing the outputs of model runs and the model responses using the variant topographic inputs.

c) The new geoinformatic layers containing surface parameters and riverbed geometry advanced the calibration procedure of a hydrological model at European scale.

d) The datasets I created are applicable to further hydrological research in potential flood damage estimation and mapping on continental level, as well as in climate change impact assessment on flood risk.

5. New research results

- Summary of frequently applied definitions and names of digital elevation models based on international and Hungarian references;
- Overview of different types of elevation models, the methodologies of their generation or sources, modelling procedures, possible operations based on the latest literature and own research experiences;
- Comparison of properties of elevation data and derived parameters based on different data sources, evaluation of their limitations from the point of view of further hydrological-environmental modelling;
- Demonstration of the limitations of global SRTM data in flood hazard mapping;
- Analyses of changes in value-set and pattern after geometric transformation (e.g. conversion between coordinate-systems) of digital elevation models of larger area;
- Contour-line-based elevation model of the Velence Mountains (Hungary);
- Description, accomplishment and visualization of the most frequently performed surface analyzing functions; examples are presented using the high resolution elevation model of the Velence Mountains (Hungary);
- Comparative description of cell-based drainage and flow models focusing on the advantages and disadvantages of their applications;
- Development of a multi-purpose geo-database of planned flood retention reservoirs in the Upper-Tisza Basin (Carpathian Mountains, Ukraine);
- Definition of capacity curves of flood retention reservoirs for hydrological modelling of impact assessment of the reservoir-system;
- First model-based impact assessment studies of the planned reservoirs;
- Discovery of numerical inconsistencies in public documentations of the New Vásárhelyi Plan;
- Drafting and testing methodological proposal for planning flood retention reservoirs in the case of the planned Szeged reservoir;
- Development and presentation of a complex approach for mapping flood hazard and flood risk providing decision support for integrated water resource management with analysis of combined results of hydraulic-hydrologic modelling, geographic-topographic conditions and actual social-economic characteristics;
- Indicating the limitations of the CORINE 2000 database as a land use data-source for setting up damage functions in order to carry out land use and water depth-based flood damage mapping;
- Development and test of methodology performing geoinformatic operations on global digital elevation models, to produce static topographic input layers for a hydrological (rainfall-runoff) model developed to simulate floods in large, continental scale river basins.

List of publications concerning the topic of the dissertation

a) Chapter in book

Mezősi, G., **Bódis, K.** (1999): Statistical Evaluation of Landscape Units, *In: Kovar, P. (Editor), 1999, Nature and culture in landscape ecology. Karolium, Prague, pp. 170-183.*

Bódis, K. (2007): High-Resolution DEM for Design of Flood Emergency Reservoirs, *In: Peckham, R., Jordan, Gy. (Eds.), 2007, Digital elevation modelling. Development and applications in a policy support environment. pp. 203-226. Springer Verlag, Berlin, ISBN: 978-3-540-36730*

Feyen, L., Dankers, R., **Bódis, K.**, Barredo, J.I., Salamon, P. (2008): Climate warming and future flood risk in Europe, *Special Issue in Climatic Change (in print)*

b) Paper

Bódis, K., Csuták, M. (2001): Using digital elevation model in geomorphology the case of the Velence Hills, *Acta Geographica, Tomus XXXVII, Szeged (Hungaria), pp. 1-10.*

Bódis, K., Szatmári, J. (2005a): Geoinformatikai döntéstámogatás síkvidéki tározók tervezéséhez, (Decision support for planning of lowland reservoirs using GIS), *Térinformatika - Hungarian GIS, 2005/5, pp. 12-13.*

c) Dissertation

Bódis, K. (1998): Geoinformatikai elemzések a Majsai-homokháton (Geoinformatics analysis on Majsa sandridge), *Diploma thesis, Szeged p. 31.*

Bódis, K. (1999): Geometriai transzformációk, transzformációs egyenletek és alkalmazásuk a geoinformatikában (Applications of geometrical transformations in GIScience), *Diploma thesis, Szeged p. 52.*

d) Publication in proceedings of international conference

Szabó, J.A., **Bódis, K.**, Tóth, S., Jakus, Gy. (2008): Impact assessment study of planned flood retention reservoirs in the Upper Tisza Basin, *In: Proceedings of FLOOD 2008, 4th International Symposium on Flood Defence, Managing Flood Risk, Reliability & Vulnerability, pp.97-1-8, 6-8 May 2008, Toronto, Canada*

e) Publication in proceedings of Hungarian conference

Bódis K., Szatmári J. (2005b): Geoinformatikai döntéstámogatás síkvidéki tározók tervezéséhez (Decision support for planning of lowland reservoirs using GIS). *Geospatial Information & Technology Association (GITA) Conference, 12-13 May 2005, Szeged, Hungary, Proceedings pp. 103-108., Szeged*

f) Scientific presentation

Bódis, K., Szatmári, J. Szakál, Sz. E., Vízhányó, J. (2003): Geoinformatikai döntéstámogatás síkvidéki tározók tervezéséhez, (Decision support for planning of lowland reservoirs using GIS), *VIII. Geomatematikai Ankét - 8th Congress of Hungarian Geomathematics, 5-6 May 2003, Szeged, Hungary*

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Szabó, J.A., **Bódis, K.** (2006): Drastic environmental interventions to mitigate floods in the Tisza Basin: Methodological study of flood risk mapping, *(Seminar, JRC IES LMNH 25/10/2006), Scientific presentation at the European Commission, Joint Research Centre, Institute for Environment and Sustainability, Weather-Driven Natural Hazards Action). Ispra, Italy.*

Szabó J.A., **Bódis K.**, Kovács S., Tóth S. (2008): A Felső-Tisza vízgyűjtőjére tervezett árcsökkentő tározók modellszámításokon alapuló hatáselemzése, (Model-based impact assessment of planned flood retention reservoirs in the Upper Tisza Basin) *Magyar Hidrológiai Társaság, Árvízvédelmi és Belvízvédelmi Szakosztály előadóülése (Proceedings of Hungarian Hydrological Society, Department of Flood Control and Land Drainage), 8 September 2008, Budapest, Hungary*

g) Scientific and technical report

Barredo, J.I., Salamon, P., **Bódis, K**. (2008a): Towards an assessment of coastal flood damage potential in Europe, *European Commission, Directorate-General Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy, p. 16. EUR 23698 EN*

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h) Map

Barredo, J.I., Salamon, P., Feyen, L., Dankers, R., **Bódis, K.**, De Roo, A. (2008b): Flood damage potential in Europe. *Catalogue number: LB-30-08-670-EN-C, JRC - European Commission, Institute for Environment and Sustainability, Map, Ispra, pp. 2.*

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