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Operational dike failure simulation

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INTRODUCTION

The hazard of dike failure poses a risk on human lives and activity in the hinterland of dikes – areas where people are protected from floods by dike constructions and usually feeling safe from that kind of hazard. Nonetheless, it is economically not feasible to provide absolute security by dikes, which are generally built to a certain design standard (Krámer & Józsa, 2004: 2). This makes respective areas vulnerable towards the inundation resulting from dike breaches, which might occur for numerable reasons, e. g. if the loading by the flood exceeds the design a dike section is constructed for. Furthermore, large stretches of dikes in many parts of Europe are not built in state-of-the-art technology and might fail due to insufficient stability even during less extreme floods (Bieberstein et al., 2007: 829-830). Numerous events in recent decades have raised social awareness of the possibility of dike breaches. This is linked to a general change in the thinking of flood management which was directed from aiming at absolute safety in flood protection to the assessment of given risk and dealing with the consequences of inundation. This risk based approach is expressed in the EU flood directive on the assessment and management of flood risk (EU, 2007).

ASPECTS OF DIKE BREACH MODELING

Dike breach induced inundation cannot be assessed by normal flood hazard maps, though. Every dike failure constitutes a unique situation which is characterized by the respective extent of inundation and distribution of water level. Merely the unpredictable breach location leads to innumerable scenarios being conceivable. Given this situation, in the conventional way a high number of scenarios would need to be pre-calculated as a preparation for such events. However, the calculation is reasonable for only a certain number of scenarios as costs and computation time increase with every simulation run. Therefore, scenario-based calculation implies high uncertainties and it is not possible to ensure that a specific real situation is reflected by the prepared hazard maps in an acceptable way in case of the occurrence of an event (Bouwer et al., 2009: 317-318). Furthermore, prepared maps often display only the maximum flood extent and inundation depths. Given the high flow velocities related to dike breaches, however, assessing flood progress is of fundamental importance regarding emergency services and evacuation (CIRIA, 2013: 949). Resulting from this complex of problems, the possibility to run a hydraulic model in operational mode is researched as an alternative way of reacting more appropriately to dike failure events. An additional enormous potential of operational inundation modelling lies in the possibility to implement intervention measures in the course of the event to assess their influence on flow behavior and flood progress.

Operational modelling signifies modelling the inundation resulting from a dike breach only when a specific event is imminent or even during the occurrence. Fast results in adequate quality are essential here. Hence, feasibility might be restricted by calculation time or the need to calculate based on coarse resolution. The necessity to assess this topic and the question in what manner to prepare such simulations in an optimal way arose during the flood event of 2013 on the river Elbe when numerous dike breaches occurred. Here, for the occurrence of two events the operational simulation of the consequences was requested. Figure 1 displays a photo of the prominent event near Fischbeck. Since the model and data had not been prepared beforehand, lack of time posed a significant challenge, primarily for the process of acquiring input data. Hereafter, within the IncREO project the general feasibility of operational dike breach induced inundation modelling was researched with the aim to develop an optimized method, that can be used to prepare for and conduct such an operation in case of a dike failure event.

Figure 1: Dike breach on the Elbe, Fischbeck, Germany. Foto: Robert Jüpner, 2013.

The transferability of the method on different potentially affected geographic regions is not only conceptual element of IncREO but central for the topic of dike failure assessment. This importance derives mainly from the high number of potential breach locations. The research was undertaken for a study area situated in Hungary where flood management relies on over 4000 km of technical infrastructure as flood protection. The studied area of Köröszug is situated in the inner area of the confluence of the rivers Körös and Tisza (s. Figure 3). Accordingly, it is entirely protected by dikes.

Figure 2: Soakejf. Source: Szféra Tisza Kft. 2012: http://harmaskoros.komplextiszato.hu/doksik/galeria_2006/flashgallery.html.

A prime example of this area potentially being affected by dike breaching is the flood of April 2006. During this extreme event several sections of the dike protecting the area of Köröszug emerged as weak points and showed cracks. Breaching could be prevented through reinforcing those sections using numerous military forces (s. Figure 2). Nevertheless, the risk of dike failure in this situation led to the decision to evacuate the 4,500 inhabitants of the potentially affected settlements. This decision could have been influenced significantly if the inundation resulting from specific breaches, which were imminent, could have been assessed.

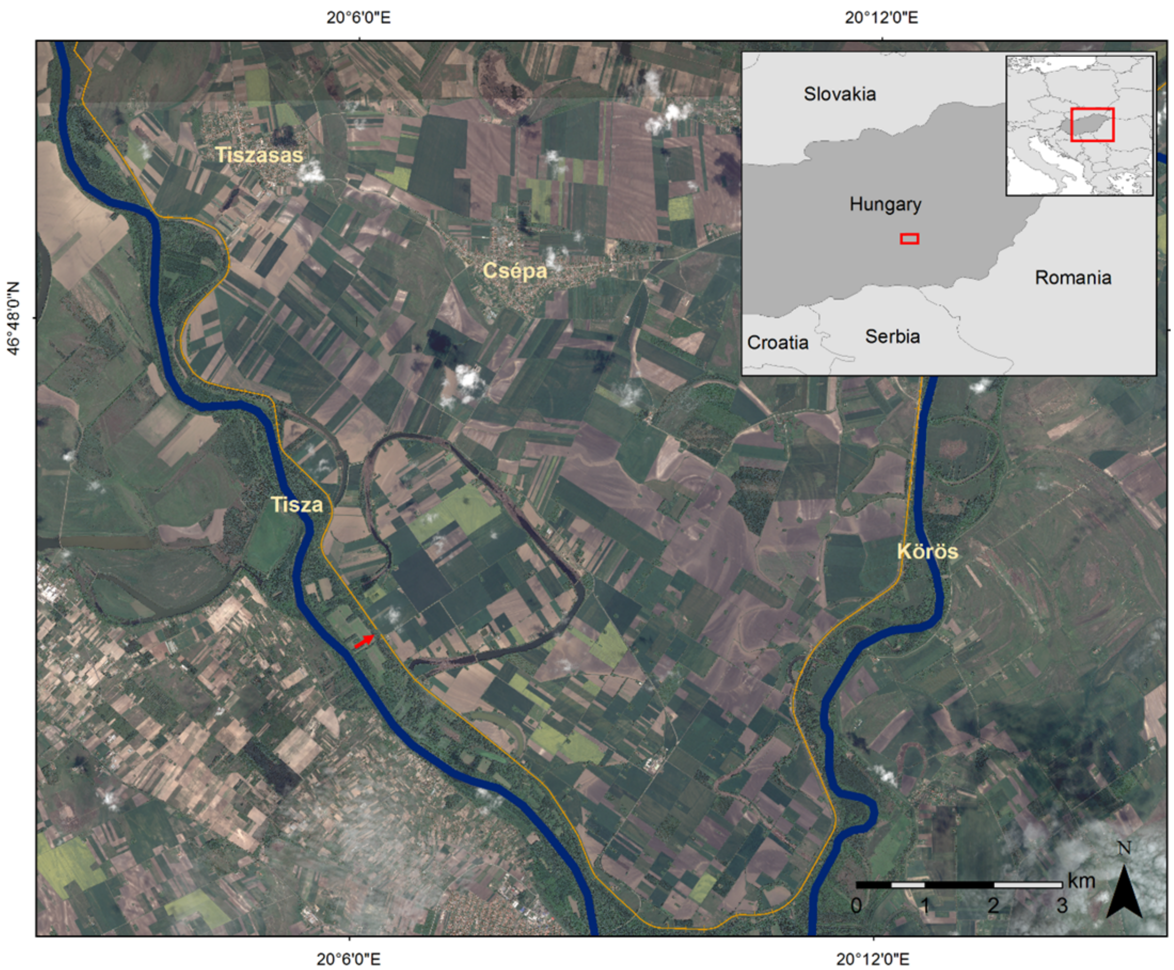

Figure 3: Overview over the study area Köröszug, Hungary, with the course of the dike (orange). The red arrow points to the scenario-defined breach location. Data: CNES, 2014.

APPROACH

For the study, terrain data of different sources was tested. Thereby, the suitability of readily available DTMs and EO-derived terrain data for hydraulic modelling in operational mode was to be assessed. At hand was a DTM provided by the Hungarian water authorities (Országos Vízügyi Főigazgatóság: OVF) in a spatial resolution of 10 m, which was digitalized from 1:10.000 topographical maps and revised based on aerial photos by the Hungarian Institute for Geodesy, Cartography and Remote Sensing (Földmérési és Távérzékelési Intézet: FÖMI). Furthermore, a DSM was generated from Pléiades stereo satellite imagery in a spatial resolution of 4 m by Spot Image SA. For the purpose of hydraulic modelling, height information implemented owing to vegetation had to be removed from the DSM. Considering the short time available in case of an imminent dike breach, the process of removing these structures of vegetation was to be largely automated. This was achieved by combining those areas which have large height offsets with areas featuring vegetation, which were derived using the Normalized Differenced Vegetation Index (NDVI) based on high resolution Pléiades satellite imagery (spatial resolution: 0.5 m; spectral resolution: 4 bands). For the assumption that areas in the hinterland of dikes usually have little relief, a correlation of existent vegetation and an exceedingly large offset in the terrain data could be interpreted as structures induced by bushy vegetation or trees. Figure 4 confirms the performance of this methodology for the study area displaying an exemplary extract. Several structures remaining in the center of larger areas affected could be removed using the RegionGroup-Tool in ESRI's ArcGIS.

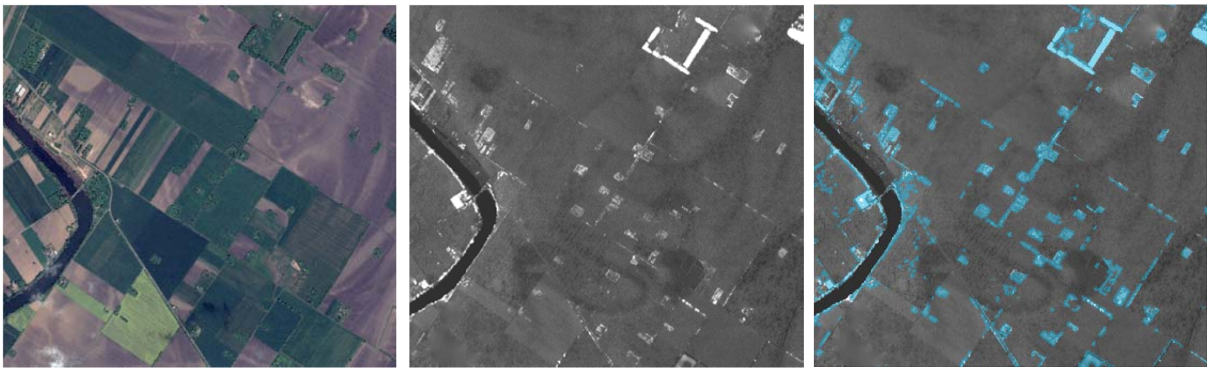

Figure 4: Extract from Pléiades satellite imagery of the study area featuring vegetation (left), resulting structures in the DSM (middle) and areas identified using the proposed method in blue (right). Data: CNES, 2014 and Spot Image SA, 2014.

Processing a DSM using only this methodology is not necessarily effectual and the results would need further revision in order to fully correct affected areas without inducing too much generalization. Nevertheless, the achieved results were used without further revision and regarded as acceptable for the intended purpose considering lack of time in operational mode. For the eventual DTM, removed areas were re-interpolated in an iterative process.

In order to optimize the methodology of the modelling itself, different parameters were varied in the course of the study. Thereby, their influence on the main factors substantial for feasibility, which are computation time and quality of results, could be assessed and analyzed in respect of cost-benefit-aspects. Modelling was performed with the raster based modelling software FloodArea^{HPC}-Desktop on a computer with 16 physical cores.
Concerning hardware, initial performance tests showed, that regarding the physical cores used a more or less linear impact on calculation time is to be expected with only minor losses arising from enhanced data transfer when using multiple cores. Thus, calculating on 16 cores is nearly twice as fast as on 8. Other hardware related performance issues that might be depending on the parameter setting in FloodArea^{HPC} are subject of further studies.

The methodology set up for modelling dike breach induced inundation in FloodArea^{HPC} is illustrated schematically in Figure 5. The water is induced into the model via the fluvial flood level which is modified in the course of the simulation corresponding to the flood progress. If the discharge through the breach can be assessed, it is alternatively possible to induce water using a hydrograph. The dike is implemented as an absolute flow barrier to avoid inflow in other parts due to inaccurate or missing representation in the terrain data. The section of the dike breach is spared out in the flow barrier, the model is based on the assumption that the dike body is completely washed away with the breach. In addition, the input of roughness values is necessary to represent the roughness coefficient in the Manning-Strickler-formula, which the FloodArea^{HPC}-model is based on.

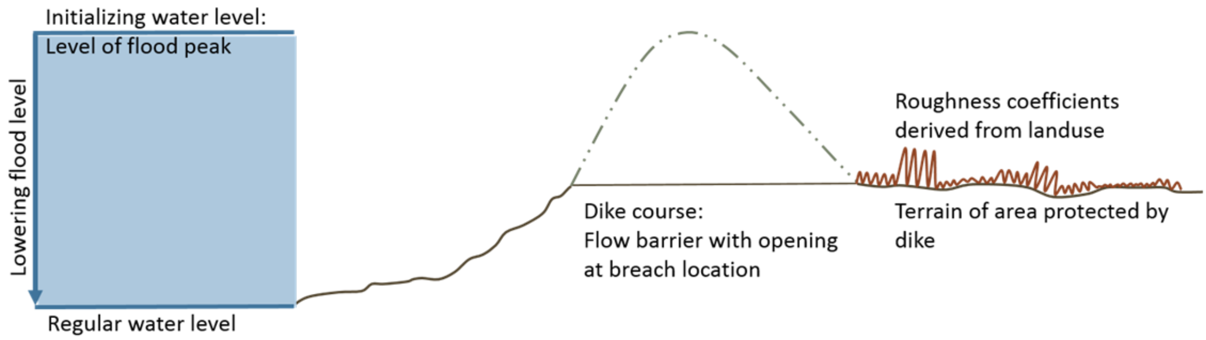

Figure 5: Model set up for modelling inundation through a dike breach in FloodArea^{HPC}. Anders 2014.

For the research in the ongoing study a scenario had to be defined, which was based on the flood levels of the extreme flood on the river Tisza in April 2006. The breach length was set to the mean value for dike breaches on the Tisza determined by a regional study (Nagy 2012). The location of the breach was set to a section where – based on detailed information of the dike structure provided for this region by the OVF – the dike crest was by far exceeded by the flood of April 2006 and therefore presumably at risk of failing.
Roughness coefficients for the model were derived from land use information in the BEAM-dataset for Hungary. BEAM (Basic European Assets Map) is a thematic map product which displays assets in monetary values per unit of area. The land use information is based on CORINE Land Cover and enhanced by HERE data. BEAM was developed within the EU-project SAFER and can be generated standardized for all European countries (Assmann & Müller, 2012: 3; Müller, Fourty & Assmann, 2013: 1046-1048). An additional run was calculated using roughness coefficients based on an enhanced land use data set for which the land use information in BEAM was revised manually based on Pléiades high resolution satellite imagery. Hereby, the influence of the accuracy and resolution of land use data on modelling results was to be assessed.

RESULTS

The results for this aspect showed a minor improvement in quality, so that it is questionable if the time required for an extensive revision is justified. Single areas might falsely be assumed affected or not affected due to lack of precision or quality in land use data. For the undertaken study this mainly concerns urban areas, which in the original data comprise agricultural or different land cover – possibly originating from administrative borders. The overestimation of the delineation of settlements in some parts leads to the result that these areas are affected by the modelled inundation (s. Figure 6). In case of a reclassification of these parts, due to then lower roughness coefficients (i.e. higher roughness values), the water does not reach the settlements in the modelled timeframe. This leads to the conclusion, that the land use information in the BEAM data generated in a standardized manner is generally suited for the purpose of operational inundation modelling. If possible, selected areas might be reclassified by involving local knowledge to avoid results leading to decisions based on inaccurate information.

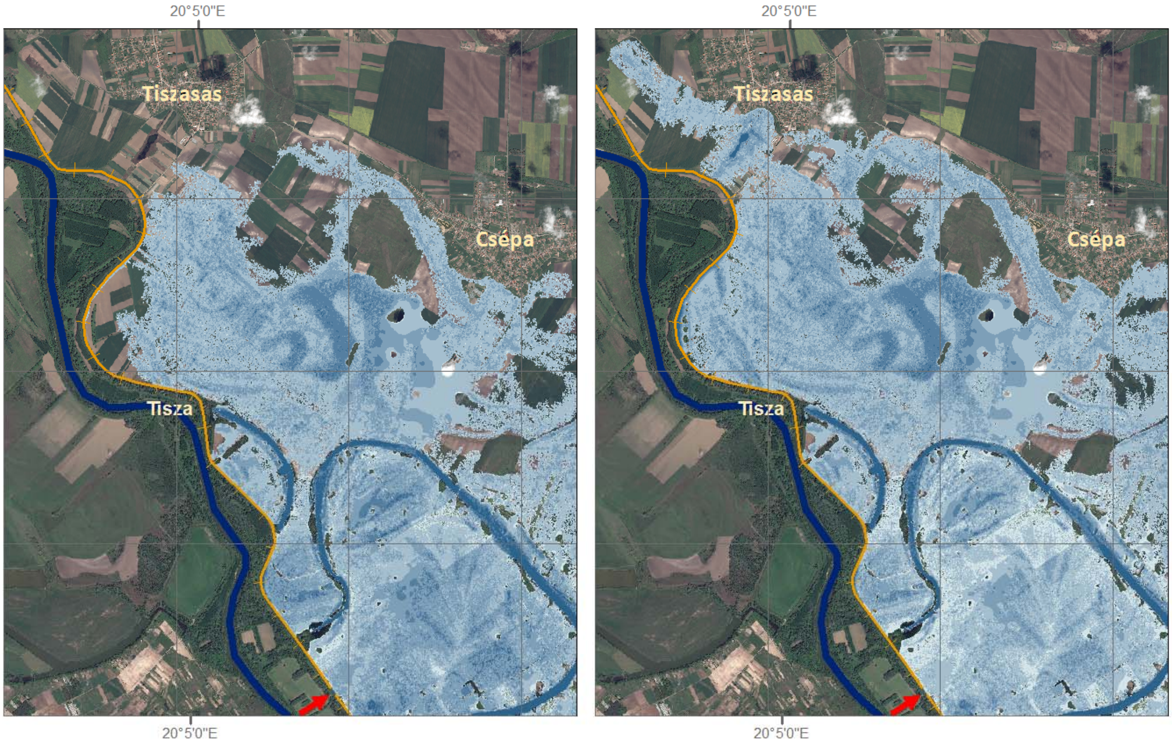

Figure 6: Extent of inundation modelling with roughness coefficients derived from reviewed BEAM (left) and standardized BEAM (left).

A very high influence on both computation time and quality of results originates from the value chosen for the model specific parameter of maximum exchange rate. This parameter in FloodArea^{HPC} determines the duration of the iteration intervals for a calculation by defining the maximum percentage of the water amount in a raster cell that is transferred from one cell to the next in each iteration step (for further introduction into the hydraulic model of FloodArea^{HPC} s. GEOMER GMBH & RZB GBR: 2011). If this value is set too high in respect of height gradients in the terrain, the model reaches its numerical limits of calculating flow directions. As a consequence, effects of forward and backward fluctuation of water might be caused in the course of modelling and lead to implausible results. Especially for the relatively plain hinterland of dikes, where moreover extremely high flow velocities occur, the emergence of such effects is highly probable if the maximum exchange rate is not set to an adequately low value. The lowest value possible is 0.1 %. Only in areas with distinct relief values of up to 5 % are viable.
The impact of maximum exchange rate on the quality of results is displayed in the figure below (s. Figure 7). The inhomogeneity of flow and massive scattering of flow directions display the implausibility of modelled flow directions using a value of 1 % in this plain area. Plausible results are displayed in the left figure using a value of 0.1 % and resulting in flow homogenously spreading from the breach location.
As a consequence, the value of maximum exchange rate for the modelling of dike breach induced inundation needs to be minimized, although the possibility to use higher values would be favourable regarding computation times. In correlation to a reduction of the value for maximum exchange rate processing times increase linearly. Hence, significant consumption of time needs to be taken into account in this respect for this study in order to ensure the quality of results. Accordingly, it is desirable to reduce processing times in a different manner.

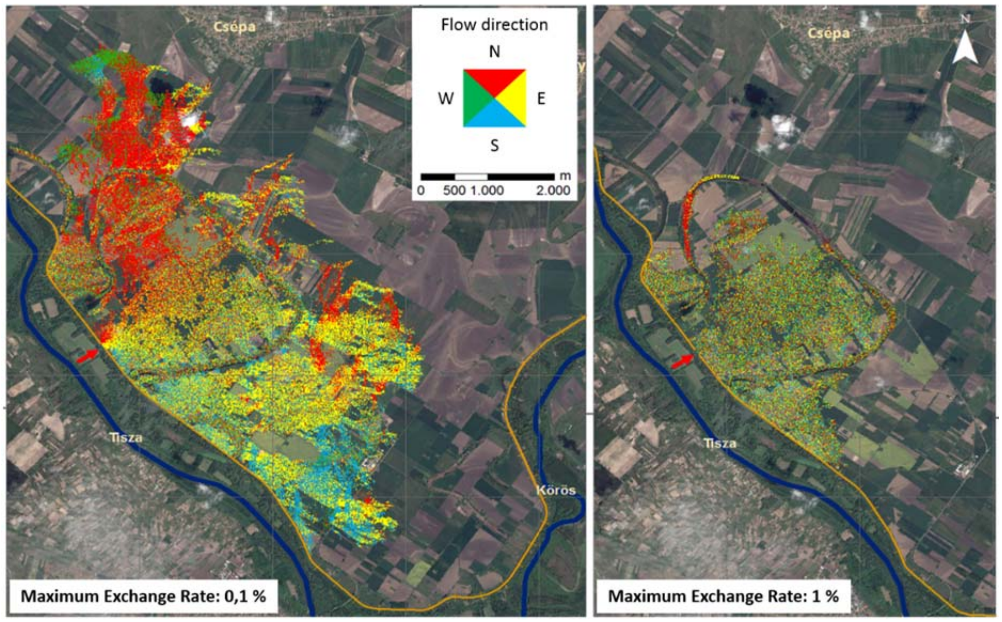

Figure 7: Flow direction 24 h after a hypothetical dike breach. Result of hydraulic modelling in FloodArea^{HPC} using maximum exchange rates of 0.1 % (left) and 1 % (right). Anders 2014.

Computation times could indeed be lowered significantly by means of a simple resampling of the EO-based DTM. Modelling results could be obtained eight times faster by reducing the spatial resolution by half, which demonstrates its enormous influence on the time needed for computation. However, the results modelled based on lower resolution generally displayed an overestimation of inundated areas as the resampling was accompanied by an overall generalization of terrain data. Thus, the resolution of terrain data proved to be of decisive importance for the accuracy, and hence quality, of modelling results. What may be regarded as minor structures, e. g. elevated road sections or trenches for (de-)watering, takes significant influence on flow behavior and should be considered in hydraulic modelling. In order to, nevertheless, decrease processing times without having to compromise the quality of results, the methodology of increasing cell width under consideration, and hence implementation, of this kind of significant structures will be matter of further research.

CONCLUSION

The studies undertaken within IncREO have shown that operational modelling is feasible depending on the pre-existent conditions and then reasonable for an enhanced assessment of event-specific dike breach induced inundation. Of special interest for users, here the Hungarian OVF, is the given possibility to consider specific intervention measures of different kinds.

In first steps an optimized model was developed for the modelling software FloodArea^{HPC}, which is flexible towards the set-up of input data at hand. Nonetheless, the study showed that certain parameters are crucial for the accuracy of results and should not be varied for the benefit of reduced processing times, e.g. the maximum exchange rate. Alternatives to reduce processing times in a reasonable manner have been proposed and will be further researched, e.g. the reduction of spatial resolution under consideration of minor structures influencing flow behaviour in hydraulic modelling. Thus, the preparation of input data and model set-up for potentially affected areas is to be generally recommended in order to enable access on a functioning system in case of an imminent event.

Availability of data and a prepared model are essential for the feasibility of operational modelling. Processing and preparing data adequately is necessary also for the conduction of scenario based modelling as a preparation for dike failure events. Seeing that, this general necessity does not pose a disadvantage of operational modelling. Operational modelling with the possibility to implement real-event parameters, therefore, poses the opportunity to enhance modelling results by using a stable model set-up in case of the occurrence of an event and by this allows both for higher preparedness and increased coping capacity. When a functioning system is prepared disaster management can make informed decisions relying on operationally produced modelling results.

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REFERENCES

Assmann, A. & Müller, M. (2012) *Where are Europe's Assets? An introduction to the Basic Europeam Assets Map (BEAM)*, Heidelberg, Immenstaad, geomer GmbH & Infoterra GmbH.

Bieberstein, A., Zesch, R., Riegger, T., Saucke, U., Scheuermann, A. & Triantafyllidis, T. (2007) *Hochwasserschutzdeiche – aktuelle Entwicklungen zur Verbesserung der Hochwassersicherheit*, *Bautechnik*, 84. Available: 10.1002/bate.200710069.

CIRIA (2013) *The International Levee Handbook,* London, CIRIA.

EU (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 Union (L288).

GEOMER GmbH & RZB GBR (2011) *FloodArea and FloodArea^{HPC}: ArcGIS – extension for calculating flooded areas, User Manual, Version 10.0 – July 2011.*

Krámer, T. & Józsa, J. (2004) *An overview of river floodplain modelling,* Budapest, Budapest University of Technology and Economics.

Müller, M., Fourty, T. & Assmann, A. (2013) *BEAM and AM+: Two assets mapping products suited for multi-risk applications*, KLIJN, F. & SCHWECKENDIEK, T. (eds.) *Comprehensive Flood Risk Management.* London: Taylor & Francis Group.

Nagy, L. (2012) *Statistical Evaluation of Historical Dike Failure Mechanism*, Riscuri Si Catasrofe, 11 (2), pp. 7-20.