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Ways for flood hazard mapping in urbanised environments: A short literature review

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Abstract: In this paper an attempt is made to present a literature review for the potential ways of flood hazard mapping in a flood prone area according to the European Directive 2007/60. These ways to produce maps are: numerical and physical modelling as well as the use of historical data mapping from records of previous extreme flood events. The use of numerical models for flood hazard map production is the dominant choice between researchers and engineers. This can be attributed to the rapid development of robust and accurate numerical models during the last decades and the low cost simulation of a possible flood event. However, the combined use of all the above ways can give a rational, realistic and accurate process for flood hazard mapping.

Keywords: Flood hazard maps, numerical models, physical models, historical data

1. INTRODUCTION

Flood is one of the most destructive natural hazard for human and physical systems. Losses of human and animal lives, destruction of infrastructure, damages to properties and the environment and negative impact on socio-economic growth are among the consequences on floods. For this reason, the European Union set in force the Directive on Flood Risk Management for the defence against floods. The basic aim of the Directive is to force the member states to devise flood risk management plans for the flood-prone areas affected by frequent and severe flood events. Flood risk maps (as an intermediate step) and flood hazard maps (as an initial step) prerequisite in order to devise such flood management plans.

It should be clarified that flood hazard maps are the maps presenting the inundation area with the maximum depths and velocities at every point of this area, whereas flood risk maps are the maps presenting the projected damage losses encountered in this area (European Council, 2007; Tsakiris et al, 2009).

The complex configuration of a typical urban area introduces uncertainties in the production of flood hazard maps. In this context, cities and towns (which concentrate the majority of the economic activity and hence flood impact becomes more severe) should have a special treatment for flood risk management plans. In this study, an effort is made to review the potential ways for flood hazard map production in an urban area, based on the existing relevant literature. The search is extended to three categories of such ways: a) numerical modelling using a specialised software, b) physical modelling with an experimental setup, c) historical data use, recorded from previous flood events.

2. NUMERICAL MODELLING

Numerical modelling is based on the numerical solution of a form of the Partial Differential Equations of Navier-Stokes equations which are in three-dimensions (3D). The most common transformations of the above equations, which describe flood wave propagation, are the following:

a) two-dimensional (2D) Shallow Water Equations (SWE) by water depth integration of Navier-Stokes equations b) one-dimensional (1D) SWE by water depth and transverse in respect to flow direction, integration of Navier-Stokes equations. The numerical solution of 1D or 2D SWE is achieved with numerical methods, namely Finite Difference, Finite Element and Finite Volume Method (Benedini and Tsakiris, 2013).

Although water flow through buildings, structures or other obstacles is a 3-Dimesnional phenomenon (Neary, 1999; Weber, 2001), a 2-Dimensional approach is also capable to simulate this phenomenon efficiently (Shettar and Murthy, 1996). It should be mentioned that the computational cost is quite high for the multi-dimensional modelling. However during the last few years, the sharp reduction of the computational cost permitted various researchers to simulate flood events in real-world case studies with 2D models. The 3D approach is still prohibitive for large scale applications.

Today a number of software packages are available, the majority of which are commercial packages with various characteristics for urban flooding simulation studies These models are based on the 2D-SWE and are known as 2D models. In this category, software packages such as MIKE21, CCHE2D, TELEMAC-2D, ISIS-2D, SOBEK, TUFLOW, RiverFLO-2D, Infoworks-2D are included (Néelz and Pender, 2009). Of course, various researchers have developed their in-house numerical models also. This is the case of FLOW-R2D model developed recently by Bellos and Tsakiris (2012). In Figure 1, indicative flood hazard maps in an urban area produced with various numerical models is illustrated.

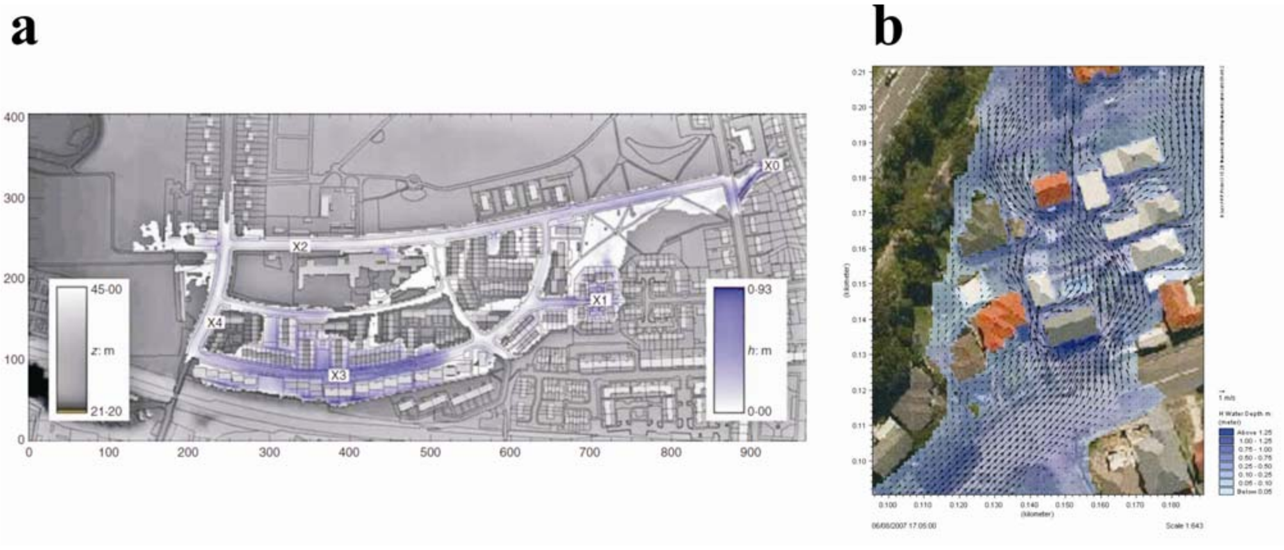

Figure 1. a) Flood hazard map with numerical model for a small urban catchment of Glasgow at Scotland (Néelz and Pender, 2009) b) Flood hazard map with numerical model for a suburb of Newcastle at Australia (Smith et al, 2012)

The most important parameter in flood modelling in urban environments is how the resistance caused by buildings or other structures is represented in the model. According to the existing literature on the subject, the most common methods for simulating the water flow among the various structures of the urban environments are the blocking-out of the solid area (which depends on the numerical method or numerical scheme used), the local elevation rise of the solid area (and hence the modification of Digital Terrain Model (DTM) to Digital Elevation Model (DEM)), and the local increase of roughness of the solid area via roughness coefficient increase.

The disadvantage of the blocking out and elevation rise methods is that they do not simulate flood flow inside the house and therefore any possible storage effects of the buildings are not taken into account. In order to avoid this disadvantage other methods have been also proposed. One of these methods consists of the representation of just the exterior walls of each building with a hole in the front wall so that water can slip inside the house. Another approach is with the DEM used combining a 'porous' approach of each building (e.g. Liang et al, 2007; Sanders et al, 2008; etc).

Flood risk can be determined based on the data exported from flood hazard maps combined with the so called depth 'damage' curves which are based on socio-economic data of the flood prone area. Scenaria which correspond to specific return periods (possibility) of flood events can be formulated with the assistance of numerical models. Then the flood risk can be determined for each return period of the phenomenon.

Lack of the appropriate field data and the low cost in comparison with the other ways are the main reasons for the dominant use of numerical models for flood hazard map production, by the majority of researchers and engineers (Abderrezzak et al, 2008).

3. PHYSICAL MODELS

The high cost of experimental process combined with the rising development of accurate and robust numerical models led the research community to the gradual replacement of the experiments by numerical modelling. The above trend does not mean that experiments have been abandoned, they have been just modified as benchmark tests for various numerical models. Moreover, numerical models cannot be considered as validated if it is not compared with at least one experiment.

Besides, physical modelling is still in use especially for practical aspects where the studied phenomenon is difficult to be numerically simulated or as an additional comparison to the numerical model's output, mainly in enormous hydraulic constructions such as dam weirs etc. It should be also mentioned that the scale ratio of geometric characteristics (length) is different in respective to the scale ratio of flow characteristics (flow velocity, roughness etc), which should be determined by Froude number constancy.

There are several benchmark test experiments for water flow through constructions or obstacles, which is the main characteristic of flood wave propagation in urban environments, reported. Studies which were conducted in the IMPACT Research Programme (for example Soares-Frazao and Zech 2007; Soares-Frazao, 2007; Testa et al, 2007) stands out whereas various researchers have validated their numerical models with the experimental results produced from the above work (Abderrezzak et al, 2008; Erpicum et al, 2010; etc).

Various researchers have also tried to simulate flood events (which have occurred or are likely to occur in the future) of real world case-studies experimentally with a physical model. Indicatively: Ishigaki et al (2003) simulated a flood prone built-up area of Kamo river (Kyoto, Japan) with an 1:100 scaled physical model. Two cases have been studied: with or without a sewer network. Hiraishi and Yasuda (2006) modelled Yokohama (Japan) port side zone (scaled 1:50) in order to examine the propagation of a possible flood wave created by tsunami. Emelen et al (2012), simulated a dike-break of Mississippi river in New Orleans (USA), after the well-known Hurricane Katrina in 2005. Specifically, a 1:50 physical model of 17th street is constructed. Water depth elevation and velocity profiles are measured in various points of the experimental setup. Tayfur et al (2013) simulated a flood wave which was propagated in Urkmez village (Turkey) and was created by a possible dam-break of Urkmez dam, with a physical model horizontally scaled 1:150 and vertically scaled 1:30 respectively. Water depth elevation and velocity profiles were measured in various points of the experimental setup as well. In Figure 2, indicative various physical models are shown.

In spite the fact that the results which are exported from physical models or other experiments are 'real', there are disadvantages. More specifically, the high cost in comparison with numerical models, the uncertainty which is created because of roughness simulation or measurement errors (which probably are more intense in shallow water depths such as water depths in experiments).

A special comment should be made about roughness representation. Generally the material which can be used in order to represent buildings, obstacles and other elements of infrastructure of an urban environment is limited in physical modelling. The most common materials are wood, steel, plexiglass and styrofoam. With these materials, an equivalent roughness should be achieved in the physical model representing the real-world case study, taking also into account Froude number constancy. Needless to say that roughness simulation inserts great uncertainties to the results of the physical model.

Finally, flood risk can be determined from flood hazard maps following the same procedure described above. Various scenaria of a flood event can be implemented in the experimental setup and then flood risk can be determined for various return periods.

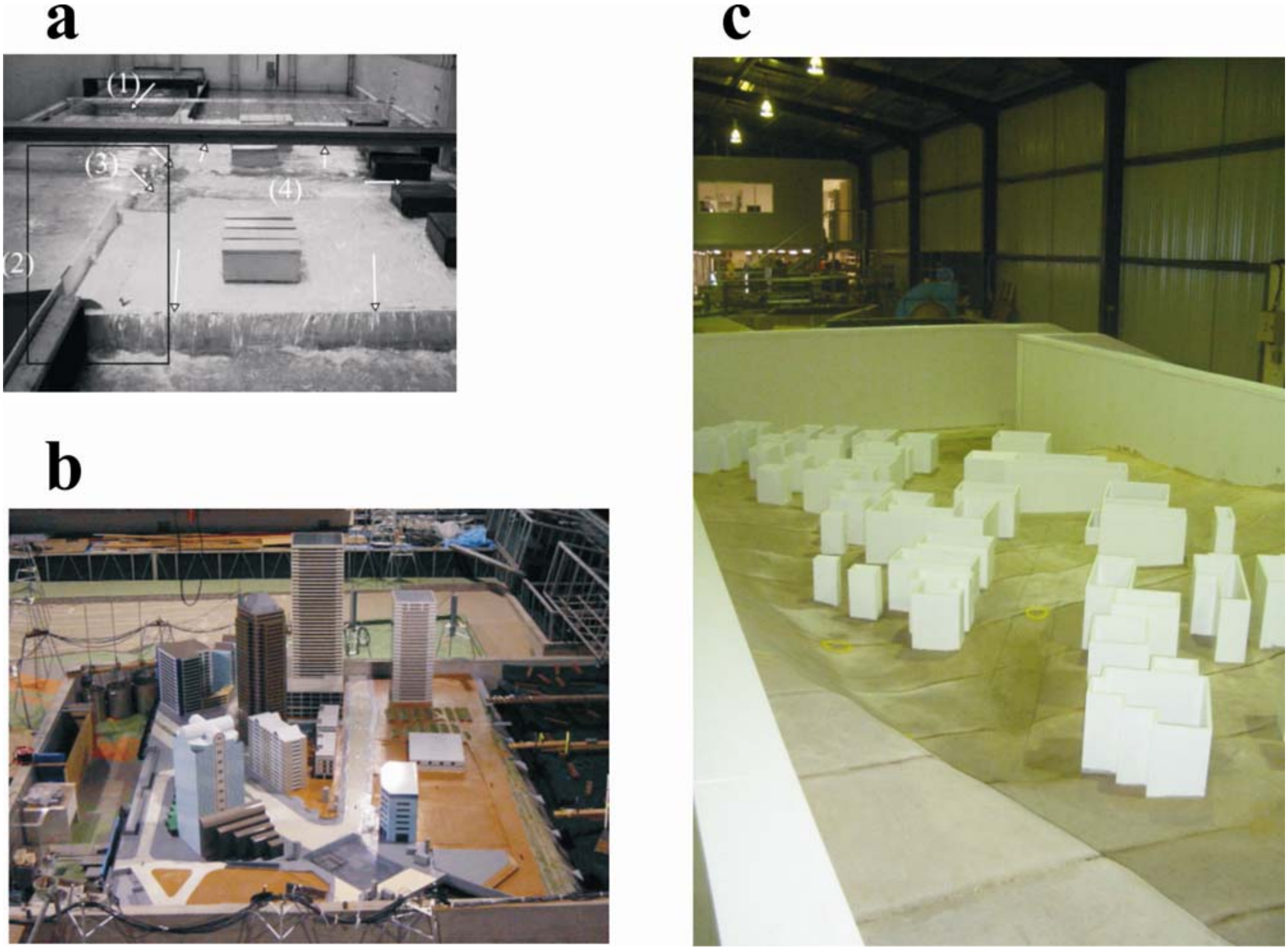

Figure 2. a) Physical model of a New Orleans (U.S.A.) street after Katrina hurricane (Emelen et al, 2012) b) Physical model of Yokohama (Japan) port side simulating a tsunami flood wave (Hiraishi and Yasuda, 2006) c) Physical model of a suburb of Newcastle (Australia) simulating a recorded extreme flood event (Smith et al, 2012)

4. HISTORICAL DATA

Historical data records from real flood events in urban areas is one of the most important and useful factor for flood hazard map production, especially for calibrating the various model's parameters, such as roughness. Besides, if a time-series record is available, historical data can be used for direct flood hazard map production for various return periods, with an appropriate statistical process (Jha et al, 2012).

In several cities in which floods are regular phenomena, state services where established in order to encounter with this hazard. For example, at Cologne city of Germany which suffered from floods created from Rhine River, Stadtentwässerungs-betriebe Köln, AöR was established, which records water elevation continuously. These records are also useful for early warning systems (Jha et al, 2012). Apart from the flood records of these cities, just a few records of extreme flood events are presented in the relative literature.

The most common source of data is field research, especially with interviews and questionnaires to the citizens of the flooded area or with the in place mark records of maximum water elevation.

Another source of data is the use of remote sensing techniques after the flood event. The majority of the available data is water elevation measurements.

There are several disadvantages for the direct flood hazard map production: a) the correlation of the data recorded from various extreme events is not guaranteed because between two flood events the potential inundated area might have a lot of changes in the infrastructure, topography etc b) in a lot of cases each flood event is unique (e.g. dam-break) c) lack of water velocity measurements results in a generally inaccurate flood risk determination, because flood risk depends both on the water depth and the water velocity values.

Carloni and Mazzanti (1964), recorded the water elevation and determined the inundated area in Piave River valley (Italy) after the flood wave propagation which overtopped Vajont dam in October of 1963. Various villages of the valley were damaged from this extreme flood event. Bosa and Petti (2011) simulated this flood event and they compared the exported numerical results with the above historical data. Taiwan City Government (2001), calculated the inundated area after a flash flood which was created by Nari typhoon at Taiwan in September of 2001. Besides pumped water volume collected from subway system and failing time of various pump stations (with known design capacity) were used in order to compare these data with a numerical model output (Chen et al, 2005). Mignot et al (2005) collected data from the Public Works Department of the Gard County and the Technical Services of Nime such as the boundaries of the flood inundated area and the direct water depth measurement in various points of the above area, after the extreme flood event occurred in October of 1988 in Nimes (France). Then, they compared these data with the results exported from their numerical simulation of this case-study. Alcrudo and Mulet (2007), presented at their work (which was included in IMPACT Research Programme), water depth elevation for various points in Sumacarcel town (Spain) which has been flooded after the wave which was created after the failure of Tous Dam in October 1982. Data were collected combining interviews and CEDEX (Centre for Studies and Experimentation of the Ministry of Public Works, Spain) reports (CEDEX, 1984; CEDEX, 1989a; CEDEX, 1989b). In Figure 3, recorded water elevations of previous flood events and a water elevation record system are shown.

Figure 3. a) Maximum water depth recorded at Sumacarcel town (Spain) after Tous Dam failure (Alcrudo and Mulet, 2007) b) Water Elevation marked after extreme flood events at a building in Wertheim town at Germany (http://www.mdweil.com/europe-cruise/wertheim-pg.html) c) Water elevation gauge of Rhine River in Cologne (http://www.steb-koeln.de/hochwasser.html?L=1)

A special reference should be made for the case-studies where a combination of historical data and results exported from a physical model is made. In December of 1959, Malpasset Dam which was constructed at Reyran River (France) failed. After the dam-break two villages were completely ruined and a lot of damages occurred in the infrastructure of the area (roads, railroad tracks). A physical model scaled 1:400 was constructed by Électricité de France (EDF) at 1964 in order to simulate this extreme flood event. The physical model was calibrated according to observed data and field measurements (Goutal, 1999). Finally, another case-study which uses the combination of historical data and physical model results is the extreme flood event occurred at Newcastle of Australia in June 2007 (Smith et al, 2012). More than 1500 flood level marks recorded by

Newcastle City Council after the flood event. Smith et al (2012) made a physical model (1:30 scale) of Morgan street of Merewether suburb of Newcastle and calibrated it using the historical data. Flow velocities and water depths were measured in various points of the experimental setup.

It is interesting to note that several researchers (e.g. Erpicum et al, 2004; Yoon and Kang, 2004) use the results which are exported from a physical model combined with results exported from field measurements, in order to validate their numerical models.

5. CONCLUDING REMARKS

In this paper, several potential ways for flood hazard mapping in the flood prone urban areas were presented in the framework of EU Directive 2007/60 and based on the existing literature. More specifically, three ways are presented and discussed: numerical modelling, physical modelling and historical data mapping with records from previous extreme flood events.

It was concluded that numerical modelling is the dominant choice for researchers and engineers in order to produce flood hazard maps. The relative low cost (in comparison with physical models) combined with the fact that they can simulate the majority of the real world case-studies, even if there is lack of data makes numerical models use preferable.

On the other hand, physical modelling can be used as an additional supportive way for flood hazard mapping, especially in very important areas where possible social and economic losses are anticipated to be very high.

Historical data mapping with records from previous flood events are very useful, especially for the calibration of the various parameters which are used by the numerical models. Besides, they give a strong indication of the magnitude of flood consequences in the studied area and assist in avoiding unrealistic simulation results. The general lack of historical data should guide the various state services to implement systematic activities of recording historical extreme flood events.

Finally, despite of the fact that numerical modelling is the most efficient way for flood hazard mapping, the combined use of all the above ways can assist in rationalising the process of flood hazard mapping.

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