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Mappings extreme floods with numerical floodplain models (NFM) in France

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ABSTRACT

For more than 20 years, hydrogeomorphological mapping in France has been considered as an efficient method of flood mapping that contributes to sustainable land development by taking into account occurrences of extreme events. The European Floods Directive (2007/60/CE) requires the production of maps showing water depths during extreme flood events. This article provides an overview of the numerical floodplain models (NFM) methodology, which uses hydrogeomorphological observations and LiDAR DEM data to produce water depth mapping. This article focuses on the NFM realised for the Meurthe River, close to the city of Nancy, France. The NFM methodology initially charts the floodplain from hydrogeomorphological mapping, then uses simple hydraulics for validation, and finally produces water depth maps with GIS processing. The resulting NFM shows good agreement with the historic 1947 flood. This methodology is a simple and complementary solution to hydraulics modelling. It provides a better way to communicate information on the extent extreme floods and shows the importance of hydrogeomorphology in flood hazard study and management.

1. Introduction

Although not new, the contribution of hydrogeomorphology to flood hazard mapping has re-emerged over the last decade because of the systemic view that it provides for the management of fluvial systems and hazards. As an alternative to hydraulic and hydrologic modelling, Wolman (1971) proposed a combination of alluvial forms analysis, pedology, and vegetation formations to delineate flood areas. Baker (1976) favoured the use of geomorphological flood hazard mapping because of its relatively low cost. Because the comparison between historic floods and geomorphologic analysis is a key element in the geomorphological mapping of the flood area, Baker (1994) also emphasized the importance of studying the morphological evidence of ancient floods to better understand current flood risks. Since these early developments, hydrogeomorphological approaches have become more widespread and are used in several countries.

In France, the study of floodplains has been the main focus of research by geomorphologists for a few decades. After studying the catastrophic floods in the French Alps in 1957, Tricart (1958, 1960) described distinctions among different alluvial beds. The methodology was considerably expanded, improved, and validated following the occurrence of several extreme floods during the 1990s and the 2000s (Arnaud-Fassetta et al., 1993; Ballais, 2006; Chave, 2002; Chave & Ballais, 2006; Delgado, 2006; Garry, Ballais, & Masson, 2002; Masson, 1993). With the aim of applying these concepts to practices, the French government decided to produce a methodological guide for hydrogeomorphological mapping (Masson, Garry, & Ballais, 1996). French hydrogeomorphological (HGM) mapping makes the distinction between major geomorphological formations and the more fine scale presence of two to three fluvial beds composing the floodplain: the minor river bed; the middle bed, which is often flooded; and the major bed, which corresponds to extreme flood events (Ballais, Chave, Delorme-Laurent, & Esposito, 2007). In addition, valley walls and old alluvial terraces are also mapped because they represent "not flooded" areas. The floodplain delimitation also relies on microtopographical analysis and sedimentological observations to increase the quality of the interpretation. Hydrogeomorphological

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mapping is now widely used in France, especially in the southern part of the country, where urban planning uses it in association with hydraulics models (Montané, Buffin-Bélanger, Vinet, & Vento, 2015).

In the province of Québec (Canada), the development of a hydrogeomorphological approach to flood hazards was initiated following a dramatic flood that occurred on the Gaspé Peninsula in 2007 (Lelièvre, Buffin-Bélanger, & Morneau, 2008). The method has undergone several modifications and improvements (Biron et al., 2014; Demers, Olsen, Dubé, Buffin-Bélanger, & Morneau, 2012, 2014; Olsen, Demers, Dubé, Buffin-Bélanger, & Morneau, 2011), thus increasing its applicability and usefulness for Québec rivers, where ice jams frequently occur. The method has been used recently in official land-use planning as an alternative to the more conventional and more costly hydraulic modelling (Besnard, 2016; Marchand, Didier, Buffin-Bélanger, & Bernatchez, 2014). Similarly, after a series of extreme flood events in Spain, several studies showed that a geographical approach combining hydrology and geomorphology was useful to prevent flood damage and promote public safety (Ibarra, 2012; Mascareñas i Rubiés, 2012). A geomorphological approach has also been used in Italy to determine flood hazards and delineate the extent of the floodplain (Morelli, Battistini, & Catani, 2014).

Within the European Union, directive 2007/60/EC, known as the *Floods Directive*[1] was adopted following the devastating floods that occurred in Central Europe in early 2000. The directive requires member states to produce flood hazard maps that include flood extent and water depths. Water depth maps are widely considered as a powerful tool for understanding flood hazards (Chau, Holland, Cassells, & Tuohy, 2013; Hubbard, Stewart, & Fan, 2014). One of the three flood scenarios required for the hazard maps is the "extreme event scenario," which is referred to as an "extreme flood" in this paper. The French government suggested that the extreme flood scenario could correspond to the extension of the hydrogeomorphological flood delineations from maps produced during the 2000s.[2] However, there is no documentation indicating what methodologies should be used to estimate water depths from the hydrogeomorphological maps.

In this paper, we propose and illustrate a methodology to produce numerical floodplain models (NFM) from hydrogeomorphological maps. NFM development is a direct response to the request by French authorities to use hydrogeomorphological mapping to identify areas at risk during extreme flood events. The NFM produced for the Meurthe River (France) was used for the extreme flood event mapping of the *TRI de Nancy-Damelevière* sector. We illustrate the method using a portion of the Meurthe River floodplain, and the results are discussed using data from historic floods. The importance of the LiDAR (light detection and ranging) remote sensing technology to produce DEM (digital elevation model) and the NFM is highlighted. Hydrogeomorphological mapping has mostly been done in French Mediterranean rivers, which are generally characterized by high-energy floodplains (Ballais, Chave, Dupont, Masson, & Penven, 2011; Garry et al., 2002; Masson et al., 1996). Thus this study also constitutes an opportunity to consider the suitability of using hydrogeomorphological mapping and the NFM methodology for low-energy rivers, such as the Meurthe River.

[1] Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007, on the assessment and management of flood risks (http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007L0060&from=EN).

[2] Circulaire du 16 juillet 2012 relative à la mise en œuvre de la phase « cartographie » de la directive européenne relative à l'évaluation et à la gestion des risques d'inondation (http://www.bulletin-officiel.developpement-durable.gouv.fr/fiches/BO201214/met_20120014_0100_0044.pdf).

2. Study area and DEM coverage

The Meurthe River in northeast France is 160 km long and a tributary of the Moselle River. The 3000 km^2 watershed includes the steep terrain of the Vosges Mountains in the north and the Lorraine plateau downstream. A major flood event occurred over the whole Lorraine region during the last four days of 1947 (Nicod, 1949). Damage from this event was heavy, especially for the city of Nancy, affecting 18,000 people and damaging 2000 buildings (DDT de Meurthe-et-Moselle, 2012). The study area is located in the downstream part of the Meurthe River, near Nancy (Fig. 1). It encompasses a 30 km section of the river with an average floodplain width of 700 m.

3. Data

The study area has complete LiDAR coverage, with 1 m data resolution. DEM data come from RGE Alti® (http://professionnels.ign.fr/rgealti). These data have a vertical precision of 0.2 m and were validated by DGPS measurements. To reduce NFM file sizes, we resampled DEM to a 3 m resolution using a bilinear resample, which is recommended for continuous data. Considering the final map scale needed for the *Floods Directive* maps (1/25 000), it represents 83 pixels per centimetre. For the hydrogeomorphological interpretation, the 3 m resolution allows for example elevation points along a topographic section at the narrowest section of the Meurthe River (600 m wide).

4. A four steps method to produce numerical floodplain models

Numerical models of flooded areas (NMFA) are developed by subtracting a DEM from a known flood surface. The NFM is a particular form of a NMFA that uses a maximum flood surface based on a hydrogeomorphological interpretation. The final result is a map of water depths corresponding to a flood that entirely fills the floodplain, hence the numerical floodplain model. The water depths map allows a quantification of what the geomorphologist observes during field work. Producing an NFM requires four major steps (Fig. 2).

4.1. Step 1: HGM mapping

The first step for producing an NFM consists of creating a shapefile in ArcGis that delimits the floodplain. Here the floodplain is defined as a subhorizontal surface surrounding the river channel that represents the extent of the highest flood for the current hydrometeorological conditions. Since the intent is to locate the floodplain's limits, the main focus remains on the principal characteristics of the surface. The delimitation of the floodplain combines a methodology using stereo aerial photography analysis, morphological indices (Ballais et al., 2011; Garry et al., 2002; Masson et al., 1996), and a LiDAR analysis procedure.

The LiDAR analysis procedure (Fig. 3) uses a combination of altitude and slope differences to visually distinguish the floodplain and the valley walls. The combination of slope and altitude has proven to be the most effective way to use LiDAR DEM to visually delimit the floodplain; this was also observed by Gallant and Dowling (2003). The slope parameter allows the slope break (>11% for the Meurthe River) to be located easily, and the discrete altitude colour scale (0.5 m interval for the Meurthe River) enables comparisons of altitude differences between several geomorphological units. In addition, topographic profiles are very useful for validating the mapping and for visualizing topographic ruptures. For example, in Fig. 3, the topographic profile shows a major elevation difference between the floodplain (<46 m) and the surface outside the floodplain, like an alluvial fan (>50 m), and the