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A DEM-based approach for large-scale floodplain mapping in ungauged watersheds

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ABSTRACT

Binary threshold classifiers are a simple form of supervised classification methods that can be used in floodplain mapping. In these methods, a given watershed is examined as a grid of cells with a particular morphologic value. A reference map is a grid of cells labeled as flood and non-flood from hydraulic modeling or remote sensing observations. By using the reference map, a threshold on morphologic feature is determined to label the unknown cells as flood and non-flood (binary classification). The main limitation of these methods is the threshold transferability assumption in which a homogenous geomorphological and hydrological behavior is assumed for the entire region and the same threshold derived from the reference map (training area) is used for other locations (ungauged watersheds) inside the study area. In order to overcome this limitation and consider the threshold variability inside a large region, regression modeling is used in this paper to predict the threshold by relating it to the watershed characteristics. Application of this approach for North Carolina shows that the threshold is related to main stream slope, average watershed elevation, and average watershed slope. By using the Fitness (F) and Correct (C) criteria of $C > 0.9$ and $F > 0.6$, results show the threshold prediction and the corresponding floodplain for 100-year design flow are comparable to that from Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps (FIRMs) in the region. However, the floodplains from the proposed model are underpredicted and overpredicted in the flat (average watershed slope <1%) and mountainous regions (average watershed slope >20%). Overall, the proposed approach provides an alternative way of mapping floodplain in data-scarce regions.

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1. Introduction

Floodplain mapping is the key task in flood risk management. Considering the disastrous impacts of floods on human lives and property, the United States Federal Emergency Management Agency (FEMA) has invested billions of dollars to create flood insurance rate maps (FIRMs) for the entire country (FEMA, 2009). FIRMs provide inundation extent that corresponds to 100-year return period flood. A similarly determined effort of floodplain mapping exists in Europe where Directive 2007/60/EC required all member states to generate these maps. (Moel et al. 2009; Van Alphen et al. 2009; EXSCIMAP, 2007). The conventional floodplain mapping approach involves both hydrologic and hydraulic modeling. A hydrologic model is used to generate hydrograph corresponding to a specific return period, which is generally 100-year. In gauged locations, flood frequency analysis can be performed using historical data to determine the design flow corresponding to a given return period. Once the design flow is known, it is fed to a 1D or 2D hydraulic model to generate water surface elevations and inundation extent for a river reach (Cobby et al., 2003; Hunter et al., 2007; Tayefi et al., 2007; Cook and Merwade, 2009; Bates et al., 2010; Neal et al., 2012; Cantisani et al., 2014).

For ungauged sites, however, there are several uncertainties and arguments regarding the accuracy of the estimated design flow based on hydrologic modeling. In these problems, a Synthetic Unit hydrograph (SUH) related to a particular return period is created based on different techniques. Singh et al. (2014) categorized the available SUH models into four groups including traditional, conceptual, probabilistic and geomorphological. They reviewed the popular methods for each group and concluded that geomorphological models are the most useful approach for prediction in ungauged basins (Grimaldi et al., 2010; Grimaldi et al., 2012; Petroselli and Grimaldi, 2015; Grimaldi and Petroselli, 2015; Rigon et al., 2016). The uncertainties associated to SUH estimation, which is the main input of a hydraulic model, is a critical issue for flood mapping in ungauged basins. In order to overcome this issue, (Grimaldi et al., 2013) proposed a fully continuous hydrologic–hydraulic modeling framework for flood mapping. In this method, instead of SUH

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estimation, a discharge time series is directly fed to a hydraulic model and the frequency analysis of the inundation area corresponding to a particular return period is implemented in the final step on the generated flood maps. Another fast and simple alternative approach for estimation of peak discharge in ungauged sites is the use of regression equations that relate streamflow statistics to watershed characteristics. For example, the StreamStats program developed by the United States Geological Survey (USGS) uses regionalized regression equations to estimate peak discharge at any location along a stream for a given return period (U.S. Geological Survey, 2012).

The conventional hydrologic and hydraulic modeling approach requires resources to collect or gather the required data and run the models after proper calibration and validation. Some of the key data include digital elevation model (DEM), land use, soil, hydrologic data, river bathymetry, and details of structures such as bridges and culverts along the reach. This approach is generally adopted for creating a flood map for individual river segments where such data either exist or can be acquired using available resources. In data-scarce regions, flood maps created through modeling can have very high uncertainty (Merwade et al., 2008). The data and computational requirements increase significantly when flood maps for tens or hundreds of reaches need to be created for a region, thus making the conventional modeling approach unfeasible for large data-scarce regions.

Absence of good datasets and computational resources has led to the development of alternative methods that process easily available public domain datasets over larger areas to create floodplain maps.

The free and widespread access to high resolution DEM for the entire globe (30 m or 90 m) in the recent years, has led to the generation of new geomorphologic Digital Terrain Model (DTM) floodplain delineation methods. The essence of these methods lies in the distinguishable geomorphic and hydrologic properties of floodplain from the neighboring hillslopes. Floodplain is the "concave depositional frequently saturated predominantly flat area" (Nardi et al., 2013) surrounding the streams. Therefore, the geomorphologic floodplain delineation methods make a preliminary estimation of potential flooding areas without considering the flood magnitudes. This is one of major differences of these methods with the conventional hydraulic modeling approaches. Although some recent geomorphic DTM-based methods are able to generate floodplain corresponding to a particular flood frequency, hydraulic models can create dynamic maps with varied inundation depth, which are event-based and are highly correlated to the flood magnitude. In one of the first geomorphic floodplain delineation studies conducted by Williams et al. (2000), the floodplain was estimated by comparing DEM and a constant water surface level for the entire drainage network. McGlynn and Seibert (2003) used a DTM-based algorithm and regional regression analysis to find the contribution of riparian area for stream networks (McGlynn and McDonnell, 2003). In another study, Dodov and Foufoula-Georgiou (2006) proposed a fast algorithm based on regional geomorphologic analysis to estimate the floodplain morphometry. Nardi et al. (2006, 2013) used a hydrogeomorphic approach that obtains the flow discharge and depth at each stream node by using the flow at the watershed outlet in conjunction with a scaling relationship based on the Geomorphologic Instantaneous Unit Hydrograph (Rodriguez-Iturbe, 1993; Rodríguez-Iturbe et al., 1979). Papaioannou et al. (2015) proposed a multi-criteria-analysis framework incorporating geographic information systems (GIS), fuzzy logic and clustering techniques to map floodplain areas at the catchment scale.

Recently some new alternative methods based on supervised classification techniques have been used for floodplain mapping. In these methods, parameters of classification are recognized by training the watershed on an available reference flood map. The trained model will be used to classify the watershed into flood and non-flood areas. De Risi et al. (2014) used topographic wetness index, derived from a DEM, in conjunction with a Bayesian updating framework to identify floodplains. Manfreda et al. (2008, 2011) used a binary threshold method in a supervised classification technique to identify flood and non-flood areas by using DEM based modified topographic index (TIm) as the classifier. Degiorgis et al., 2012, investigated the performance of binary threshold methods by creating several classifiers based on a single morphologic feature, including the distance from a DEM cell to the nearest stream (D), difference of elevation between a given cell and closest stream (H), surface curvature (ΔH), contributing area (A) and local slope (S). They demonstrated that the topographic feature, H, defined as the difference in elevation between a given cell and the nearest stream is the most significant morphologic feature for floodplain mapping using binary classifiers. Further studies on performance of single or a combination of multiple morphologic features also proved the effectiveness and applicability of feature H for flood mapping in supervised binary classification methods (Manfreda et al., 2015, 2014; Samela et al., 2016). It should be noted that Feature H firstly defined as an effective hydrologic descriptor by Rennó et al. (2008) and its application in the prediction of hydrologically relevant soil environments was investigated (Nobre et al., 2011).

Despite the advantages of the proposed geomorphic DTM-based methods for simple and preliminary large-scale flood mapping, the applicability and effectiveness of them is still controversial for data-scarce regions. For example, the supervised classification methods are all dependent to a reference map for training but these maps area not available in many areas which results in limiting the application of these methods for ungauged watersheds. Moreover, the methods based on regional regressions analysis, which relate the floodplain geometry to contributing area, require large survey datasets, which are not available for many rivers. In one study Sangwan and Merwade (2015) used a simple GIS-based attribute query on the SSURGO soil database in the U.S. to map floodplains in Indiana, which was then expanded for the entire U.S. (Merwade et al., 2015). Although this work and some other studies such as clustering methods and older low-valley detection approaches can be applied for any ungauged watershed, there are many assumptions and high uncertainties in the structure of such methods. Furthermore, they are not able to account for floodplain related to a particular flood frequency, which limits their applications for flood risk management purposes.

The main limitation of supervised classification methods is that the training data should be an appropriate indicator of the entire data with the same properties. In the case of flood mapping, it means that the training area with available reference maps and the test area should have identical geomorphologic and hydrologic behavior. Therefore, the threshold estimated from training area can be used in the test area (Threshold transferability assumption). In a small scale problem, floodplain for some unknown areas in the watershed (test area) is predicted by calibrating the classifier on a portion of watershed with available reference maps (training area). While the threshold transferability assumption for such a small scale floodplain mapping (a watershed is the study area) is almost met, making this assumption for large scale problems can be controversial. In a recent study by Samela et al. (2017), the supervised classification method was used to predict floodplains in ungauged watersheds. The threshold that was derived using reference maps in data-rich watersheds was applied for the entire study area including the ungauged watersheds. The threshold transferability assumption which consider similar geomorphologic and hydrologic behavior for a large heterogeneous study area, negatively influence the accuracy of the predicted floodplains. In this study, we aim to overcome this limitation of supervised clas-

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