Journal of Hydrology 458–459 (2012) 68–86

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Probabilistic flood inundation mapping of ungauged rivers: Linking GIS techniques and frequency analysis

Ali Sarhadi [a,*], Saeed Soltani [a], Reza Modarres [b]

[a] Department of Natural Resources, Isfahan University of Technology, PO Code 8415683111, Isfahan, Iran
[b] Institute national de la recherche scientifique, 490 rue de la couronne, Québec (Québec), Canada

ARTICLE INFO

Article history:
Received 3 October 2011
Received in revised form 10 June 2012
Accepted 20 June 2012
Available online 28 June 2012
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Axel Bronstert, Associate Editor

Keywords:
Flood hazard mapping
Ungauged reaches
High resolution Cartosat-1 based DTM
HEC RAS
Flood frequency analysis
Arid regions

SUMMARY

This study presents an exhaustive methodology of floodplain mapping at ungauged rivers. To present our methodology, we selected the Halilrud basin and Jiroft city in southeastern Iran as an example of hazardous regions. To estimate flood quantiles in different return periods at ungauged reaches, we used regional flood frequency analysis. By using the well-known L-moments approach and related criteria, a homogeneous region was formed and the 3-parameter Log normal distribution was identified as the robust regional frequency distribution. The hydro-geomorphic characteristics and the land use properties of the catchments were then extracted using RS&GIS techniques to establish multivariate regional regression models between hydro-geomorphic characteristics and flood quantiles. After delineation of the catchments for the ungauged reaches, flood quantiles as an important factor in flood inundation at outlets of these reaches with different probabilities were estimated using the regional regression models. To delineate flood hazard maps and to enhance the accuracy of the hydraulic modeling, we applied satellite stereoscope images of Cartosat-1 along with the Rational Polynomial Coefficients to extract a high resolution DTM and detailed parameterization of the channel required by 1D hydraulic model HEC-RAS. The GIS-based HEC-Geo RAS pre- and post-processor were also used for careful optimization of the geometry features for real visualization of the flood prone areas. Information of some historical flood events was also used to evaluate the hydraulic model performance in predicting flood inundations. Finally, vulnerable areas were crossed with extracted land use mapping from IRS-P6 satellite images to differentiate the critical infrastructures and the valuable land use classes affected by floods in different return periods.

1. Introduction

Floods are among the most devastating natural disasters in the world, claiming more than 20,000 lives per year and adversely affecting about 75 million people world-wide, mostly through homelessness (Smith, 2001). As the severity and frequency of flood events have considerably increased, there is a growing global concern about the need to decrease flood related fatalities and associated economic losses. Identifying prone areas can therefore be one of the key solutions in flood mitigation. Predicting susceptible floodplains and high potential flash flood prone areas can help authorities in planning management strategies for flood mitigation such as designing water control structures (reservoir levee projects), decision making for flood insurance and facilitating emergency preparedness to cope with flooding (Sanders, 2007; Srinivas et al., 2008).

To identify flood prone areas, a model is required to predict spatially distributed estimates of the hydraulic variables such as flood inundation extent and depth. 1D and 2D dimensional hydraulic models are now widely used for this purpose. These models are able to compute water surface profiles rapidly in several different characterizations of the system. Recently developed tools for hydraulic modeling are Geographical Information System (GIS) (Casas et al., 2006; Merwade et al., 2008) and Remote Sensing (RS) techniques (Chormanski et al., 2011; Straatsma and Baptist, 2008) that allow one or two-dimensional representation of the computed hydraulic parameters. In hydraulic modeling, two critical factors: (i) streamflow data (flood quantiles), and (ii) topography of river channel (Horritt and Bates, 2001) influence flow hydraulics and the resultant areal extent of the simulated flood inundation.

Almost all studies in identifying floodplain inundation areas have been carried out at gauged rivers or have been done based on available flow information of upstream station(s) (Aggett and Wilson, 2009; Bates et al., 2006), even though many flood prone regions include large population centers or precious land uses suffer from a lack of site-specific records upstream. The lack of data for ungauged rivers often deprives researchers to have an accurate prediction of flood magnitude as a key factor for a reliable flood inundation mapping.

* Corresponding author. Tel.: +98 311 3912841x1029; fax: +98 311 3912840.
E-mail address: alisarhadi2005@gmail.com (A. Sarhadi).

0022-1694/$ - see front matter
http://dx.doi.org/10.1016/j.jhydrol.2012.06.039

Nomenclature

DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DTMs	Digital Terrain Models
GCPs	Ground Control Points
GIS	Geographical Information System
LCk	L-Coefficient of Kurtosis
LCs	L-Coefficient of Skewness
LCv	L-Coefficient of variation
LiDAR	Light Detection and Ranging
MDP	Maximum Daily Precipitation
LMRDs	L-Moment Ratio Diagrams
MRRA	Multivariate Regional Regression Analysis
MRRMs	Multivariate Regional Regression Models
RFFA	Regional Flood Frequency Analysis
RPCs	Rational Polynomial Coefficients
RS	Remote Sensing
SAR	Synthetic Aperture Radar
VIF	Variance Inflation Factor

Flood magnitude prediction at ungauged reaches is an important task in designing river engineering and hydraulic structures and remains a fundamental challenge for hydrologists (Li et al., 2010). At ungauged basins, hydrological regionalization is usually applied as a reliable method for the estimation of the hydro-climatic variables at different return periods in the site of interest (Hosking and Wallis, 1997). Regionalization transfers hydrological information from one or more gauged catchments to geographically contiguous (or non-continuous) regions and hydrological neighborhood ungauged catchments of interest (Ouarda et al., 2001) by extrapolation using remote sensing data, hydrologic model simulation and integrated meteorological and hydrological modeling approaches (Goswami et al., 2006).

Regional Flood Frequency Analysis (RFFA) comprises two main steps: delineation of the groups or regions of the hydrologically homogenous catchments, and estimation of the regional flood quantiles at different return periods for the region of interest (Ouarda et al., 2006; Sarhadi and Modarres, 2011). The homogeneity of a group of sites is a fundamental requirement for performance of an effective regional estimation of the exceedance of the flood events (Castellarin et al., 2008). Hydrologists have proposed a number of tests and analyses to check the homogeneity of hydrological variables. One of the first statistical tests based on the variability of sample coefficients of variation and/or skewness among sites, was proposed by Dalrymple (1960). Then Lu and Stedinger (1992) suggested a homogeneity test according to the variability of normalized at-site Generalized Extreme Value (GEV) distribution flood quantiles. L-moments method introduced by Hosking and Wallis (1993) is now widely used by hydrologists to test the regional homogeneity of hydro-climatic variables. Hosking and Wallis (1993, 1997) proposed heterogeneity statistics for the estimation of the degree of heterogeneity in a group according to the intersite variability of L-moment ratios. In comparison to conventional moments, L-moments are superior to the product moments in that the former are more robust in the presence of outliers and less subject to bias estimation, and of course do not suffer from sample size related bounds as well.

To estimate the probability of the exceedance of the flood quantiles at the particular ungauged sites within each delineated homogenous region, several regional approaches have been established. Some of them consist of pooling hydrologically similar catchments into a homogeneous group and subsequently using averages within each pooling group to estimate flood probabilities in target catchments, such as the Index Flood (Dalrymple, 1960; Singh, 1992), and the Region of Influence (ROI) (Burn, 1990; Pfaundler, 2001) approaches. The other alternative approaches are based on application of geostatistical methods, which use spatial proximity as a measure of hydrological similarity (Merz and Blöschl, 2005). An extensive review and comparative evaluation of different regionalization methods is found in the study of GREHYS (1996).

Perhaps one of the earliest and the most widely used methods applied to estimate hydrological variables at ungauged sites is Multivariate Regional Regression Analysis (MRRA), which uses flood quantiles and catchment attributes (Chiang et al., 2002; Pandey and Nguyen, 1999; Vogel et al., 1999). In regional flood quantiles estimation, a power-form equation is generally used to relate flood quantiles of interest to catchment physiographic, geomorphologic and climatic characteristics. Because of their easy application, regional regression models have been recently applied not only for flood flow prediction at ungauged sites (Rao and Hamed, 1997; Vogel et al., 1993, 1999), but also for low flow prediction (Chen et al., 2006; Kroll and Vogel, 2002; Modarres, 2008) and hydrological drought analysis (Modarres and Sarhadi, 2010).

In this study, we link an L-moments approach and parametric regional regression models for flood quantile estimation via a catchment's characteristics. In this way, Multivariate Regional Regression Models (MRRMs) allows an estimation of the flood quantiles in different return periods at ungauged reaches of interest as probabilistic scenarios for simulating floodplain inundations.

Besides flood quantile estimation, the second issue in hydraulic modeling and predicting flood inundation mapping is the quality and accuracy of the topographic data source (Sanders, 2007). In flood hydraulic modeling, the resolution of the topographic data is a key element (Sanders, 2007), so small errors in topography affect the accuracy of the hydraulic model prediction (Aronica et al., 1998; Finlayson and Montgomery, 2004; Wilson, 2004). Traditionally, topographic surveys and manual interpretation of the terrain maps, which are limited by serious time and expense constraints (Marche et al., 1990; Nardi et al., 2006), were used as the only available method for terrain modeling. However, the availability of the digital terrain information and spatial modeling tools in GIS has made it possible for researchers to utilize Digital Terrain Models (DTMs) to investigate the effects of a channel's spatial variability on prediction of the flood hazard mapping. More recently, the advancement of RS technology has provided new capabilities that improve the quality of floodplain inundation mapping. The most promising data sources are Light Detection and Ranging (LiDAR) (Aggett and Wilson, 2009; Webster et al., 2004) and Synthetic Aperture Radar (SAR) data (Martinez and Toan, 2007; Schumann, 2007), which provide effective topographic datasets for the specific requirements of hydraulic modeling. Currently, the use of DTMs for hydraulic modeling is conditioned by their availability or by the economic factors (Cobby and Mason, 1999; Gomes Pereira and Wicherson, 1999). As high-resolution elevation data are costly and currently available for only a limited number of rivers, in this study we introduce an alternative remote sensing-based technique for extracting highly detailed topographic datasets that increase the accuracy of hydraulic modeling.

The aim of this study is to present an efficient methodology for the delineation of the flood hazard mapping at ungauged rivers.