Floodplain Morphometry Extraction from a High Resolution Digital Elevation Model: a Simple Algorithm for Regional Analysis Studies

B. A. Dodov and E. Foufoula-Georgiou

***Abstract*—In this paper we introduce a fast algorithm for floodplain delineation. The underlying assumption of the proposed procedure is that the inundation depth used to define the lateral extent of the "geomorphologic floodplain" is proportional to the depth of the channel at bankfull flow, a relationship which emerged from a detailed and objective regional analysis. Bankfull and floodplain geometry extracted with the proposed algorithm over a wide range of scales revealed important connections between fluvial and hydrologic processes and showed that the nature of these connections is scale-dependent.**

***Index Terms*—Digital Elevation Model, Floodplain, Geo-morphologic analysis, Hydrology.**

I. INTRODUCTION

Floodplain delineation procedures have been traditionally related to flood risk management and, as such, they require maximum precision in order to optimize the local insurance and reinsurance policies. The traditional floodplain delineation approach typically considers the floodplain inundated by a flood peak of particular magnitude corresponding to a given return period (i.e. the number of years within which such an event will be equaled or exceeded once, on the average) using one-dimensional river hydraulics models such as HEC-RAS (US Corp. of Engineers), MIKE11 (Danish Hydrologic Institute), SWMM-EXTRAN (US Environmental Protection Agency), etc. After the free water surface is obtained from a river hydraulics model, it is extrapolated (and/or interpolated) over the Digital Elevation Model (DEM) of the terrain and all submerged parts of the terrain surface are assumed to be part of the floodplain (e.g. see [6] for technical details). Since the simulation of stream hydraulics based on the full dynamic St. Venant equations is computationally expensive and a data-demanding process even in the one-dimensional case, hydraulic simulations (and respectively floodplain delineation) are usually performed with respect to separate river reaches or part of the network but not with respect to the whole stream network.

In contrast, the purpose of a regional geomorphologic analysis is to: (i) define the extent of the natural variability envelope of channel and floodplain morphologies (both cross-sectional and planform) as they vary with contributing area, and (ii) quantify the multidimensional statistical dependencies between these morphologies over a large range of scales within regions of similar climatic and geologic conditions. Immediately, it becomes clear that the implementation of the "traditional" floodplain delineation approach would be infeasible for such an analysis as one has to consider scales (contributing areas) from one to hundreds of thousands of square kilometers. In addition, since in a regional geomorphologic analysis the emphasis is on the statistical properties of the factors describing channel and floodplain morphologies (i.e. distributions, moments and covariance structure) the local precision of the floodplain determination is a second order concern. Finally, in a regional geomorphologic analysis one is interested in floodplain morphology defined with respect to the floodplain's natural boundaries (which are static and in most cases can be well identified based on geomorphological grounds) rather than in the part of the floodplain submerged during an event of particular magnitude (these boundaries are transient and dependent on the flood magnitude). We will refer to the former as the "geomorphologic floodplain" (GF) and to the latter as the "submerged floodplain" (SF). This paper is concerned with the GF and proposes a fast procedure for its delineation.

II. REGIONAL GEOMORPHOLOGIC ANALYSIS

As the GF is essentially formed by lateral migration of channels and controlled by the water and sediment transport in a river, it is reasonable to assume that the channel and GF geometries (and particularly depths) are closely related. With an increase of contributing area and channel bankfull discharge, thin and narrow floodplains are replaced by wider and flatter floodplains of increasing thickness and inundation. Deeper inundation in turn provides more overhead cover and greater channel depth. Intuitively, this line of thinking suggests a close connection between channel depth at bankfull and GF inundation depth (see Fig. 1). Although such an intuitive connection is in general accepted by geomorphologists (personal communication with *Gary Parker*, *Chris Paola*, and *Kelin Whipple*, 2004) to the best of

Manuscript received October 27, 2004.

B. A. Dodov is with Applied Insurance Research Corp., 131 Dartmouth St., Boston, MA 55414, USA. (e-mail: bdodov@air-worldwide.com).

E. Foufoula-Georgiou, Co-Director, National Center for Earth-surface Dynamics (NCED), St. Anthony Falls Laboratory, University of Minnesota Mississippi River at 3rd Avenue SE, Minneapolis, MN 55414, USA. (corresponding author, e-mail: efi@tc. umn.edu).

our knowledge it has never been supported by a quantitative geomorphologic analysis. Below, we provide such an analysis showing not only a close connection between bankfull channel and GF inundation depths, but also that the emergent relationship is linear to a good approximation over a range of scales.

Before continuing with our analysis, we first need to establish a connection between channel bankfull depth D_{bf} at a given point in the network and the contributing area draining to this point (referred to as "scale" in the sequel). For the extraction of such a relationship we analyzed independent measurements of stage, maximum width, depth and discharge under different flow conditions (up to several hundred measurements per station) from 113 USGS gauging stations in Oklahoma and Kansas (see Figs 1-3 in [3])). Bankfull conditions were considered to occur when a break in slope was observed in both stage-discharge and width-discharge relationships (see Fig. 5 of [3]). For small contributing areas, bankfull geometry derived from field observations was added to increase the reliability of our analysis. In Fig. 2a we plot channel depths at bankfull as a function of contributing area. As can be seen, the relationship can be well approximated as log-log linear (solid line) with a break at approximately 700 km^2.

Having established the scale-dependence of bankfull channel depth, we proceed with the analysis of the connection between the depth of a channel at bankfull and the corresponding GF inundation depth. For this analysis, we applied the floodplain delineation procedure described in detail in the next section on the high resolution National Hydrography Data (NHD) of the Neosho River basin (see Fig. 2 of [2]) for 25 log-uniform scale intervals between 1 and 15,000 km^2 and log-uniform inundation intervals between $0.1D_{bf}$ and $3D_{bf}$. In Fig. 2b we plot the relative floodplain area (RFA: area of the submerged floodplain SF corresponding to a particular inundation depth divided by the area corresponding to the maximum considered depth of inundation, i.e. $3D_{bf}$ in our case) as a function of inundation depth for two scale intervals log-centered at approximately 9 and 9000 km^2. A break is observed in each of these relationships denoting that below and above the break the rate of increase of the submerged surface for a given rate of increase of the inundation depth changes. The depths at which these breaks occur were interpreted as the inundation depths defining the lateral extent of the GF at a given range of scales. Curves such as that of Fig. 2b were examined for all the 25 scale intervals and the inundation depths corresponding to the breaks were extracted. These depths were then plotted in Fig. 2a as a function of scale (solid circles) and compared with the bankfull depths (open circles). It is interesting to observe that a linear relationship between the two depths emerged $D_{gf,in} = pD_{fp}$ with a coefficient of proportionality p = 0.6, empirically derived. The above analysis puts on solid grounds the commonly used rule of thumb that the GF inundation depth is a percentage of the bankfull depth and provides an objective way of estimating the proportionality coefficient for the region of interest. This relationship was adopted in our GF extraction procedure explained in detail in the next section.

It is noted that $D_{fg,in}$ (as extracted from several curves such as those shown in Fig. 2b) was found to scale with drainage area as $D_{gf,in} \sim A^{0.35}$ for small areas and $\sim A^{0.05}$ for large areas (see solid circles in Fig. 2a). One can argue that these regional relationships, which need only drainage area, could be used directly for prediction of $D_{gf,in}$ without the need to use the relationship $D_{gf,in} = pD_{fp}$. We argue that the latter relationship, which depends on the local values of D_{bf} but has used regional information to estimate the proportionality constant p would be preferable and more accurate locally if site-specific D_{bf} values are available from high resolution DEMs or from local surveys.

III. Floodplain Delineation

A. Geomorphologic Floodplain (GF) Delineation

The idea of the GF delineation algorithm is to locally "fill" the DEM up to the depth of inundation of the GF using an horizontal disk centered at pixels along the river network. First, the depth of inundation and therefore the water surface elevation of the GF is determined at points along the river network using the concepts of section II. Then, the lateral extent of that water surface, and therefore the lateral extent of the GF, is determined using planform curvature characteristics of the channel. In particular, an horizontal disk was centered at each point along the river network resting at the elevation of the GF water surface. The radius of the horizontal disk was chosen proportional to the median radius of the channel planform curvature at any scale (see below for explanation) and then all the pixels covered by the disk and with elevations less than that of the disk were assumed to belong to the GF.

The median radius of curvature criterion was chosen because this parameter was considered the one which is most related to the width of the GF. Since the computed extent of the GF is much less sensitive to this parameter compared to the depth of inundation, only a trial and error procedure was applied for its determination (essentially, the only requirement in this case is that the diameter of the "disc" function has to be larger than the width of the GF at a given scale). The relationship between channel planform curvature and contributing area was extracted from high resolution hydrography data of the Neosho River basin and approximated by a power-law (see Fig. 3 and also [2] for details).

In summary, the GF delineation algorithm consists of the following:

a) Input data: DEM grid and Area Accumulation Grid (AAG).
b) Choice of an appropriate number of scale ranges. Areas less than 1 km^2 should not be considered since the resolution of the DEM does not allow proper treatment of floodplain cross-sectional shapes for such contributing areas.

c) Determination of the set of all pixels assigned to the GF with contributing areas within specified ranges (or equivalently topological Strahler order ω; see Fig. 8d of [2]).

B. Floodplain skeleton extraction

For the extraction of the floodplain skeleton the so-called medial axis transform was used (e.g. see [7]). The procedure consists in the following: for every pixel from the floodplain calculate the unit vector pointing to the nearest pixel on the floodplain boundary grid FBG. Calculate the maximum angle between a given pixel's unit vector and the unit vectors of the surrounding pixels. The skeleton is formed by pixels with maximum angles larger than $\pi/6$. More specifically the steps in this procedure are:

a) Compute the direction grid DG from the floodplain boundary grid FBG (i.e. from every pixel on the floodplain to the floodplain boundary).
b) Derive the skeleton grid SKG from the direction grid DG.

After the floodplain skeleton is derived, it is vectorized using the public-domain WINTOPO software and transformed back to raster format in order to: (i) "thin" the skeleton, (ii) clean all branches and noise pixels not connected to the floodplain network.

C. Floodplain centerline extraction

In order to properly analyze the variation of floodplain width as a function of contributing area, the branches within the floodplain have to be removed (e.g. pixels with contributing area 3 km^2 cannot have 2 km wide floodplain). To do this, we take every pixel in a given range ω and compute its distance to the nearest pixel of range larger than ω (higher order pixel). If this distance is less than the distance from the higher order pixel to the floodplain boundary, the pixel of range ω is removed from the skeleton. An example showing the skeleton and the GF centerline is not given here due to space limitations but can be found in Fig. 19 of [3].

IV. Floodplain Geometry and Regional Flood Frequency Analysis

Since every pixel of the GF centerline can be assigned an elevation, a contributing area, a distance and a direction to the floodplain boundary, we can compute the GF transverse slope from (DEM) profiles and perform statistical analysis of properties for any range of scales. In Fig. 4 (top left panel) we plot the median floodplain half-width as a function of scale (median because the distributions of the floodplain widths and transverse slopes are skewed) together with the coefficient of variation CV (standard deviation divided by the mean) of the maximum annual peak discharges (bottom panel) for 72 out of the initial 113 stations. Compared with Fig. 2a these plots clearly suggest a common break in channel/floodplain geometries at the scale of approximately 700 km^2 (see also [3] for quantification of the physical and statistical significance of the break), which obviously affects the relative variability of flood peaks in a different way below and above the scale of the break.

To further support the importance of the GF geometry analysis on flood statistics let us consider another region with different geologic and climatic conditions, namely, the Appalachian region in the Eastern US. In their work Smith [8] and Gupta et al. [4] showed that the CV of maximum annual floods for 104 stations in this region increases up to approximately 100 km^2 and then decreases (see Fig. 4 bottom right panel). The result of our floodplain geometry analysis in Fig. 4 (top right panel), showing a break at 100 km^2, once again supports the close connection between floodplain geometry and streamflow variability. It is noted that the scale of the break is different in the Oklahoma-Kansas and Appalachian regions as the physical mechanisms responsible for the feedbacks between fluvial and hydrologic processes differ significantly between these two regions.

V. Summary

This work proposes a simple and fast algorithm for geomorphologic floodplain (GF) delineation and analysis based on morphometric considerations. The proposed algorithm was applied in several basins in Central (Oklahoma, Kansas) and Eastern (Appalachian Region) United States. Combined with a regional flood frequency analysis, an important interplay between hydrologic and geomorphologic processes, which changes character with scale, was revealed.

Acknowledgment

This research was supported by the National Center for Earth-surface Dynamics (NCED), an NSF STC, under agreement EAR-0120914. Computer resources were provided by the Minnesota Supercomputing Institute (MSI). We thank an anonymous referee for helpful suggestions.

References

[1] Dodov, B., and E. Foufoula-Georgiou, Generalized hydraulic geometry: Derivation based on a multiscaling formalism, *Water Resour. Res.*, 40 (6), W06302, doi:10.1029/2003 WR002082, 2004a.
[2] Dodov, B., and E. Foufoula-Georgiou, Generalized hydraulic geometry: Insights based on fluvial instability analysis and a physical model, *Water Resour. Res.*, 40(12), W12201, doi:10.1029 /2004WR003196, 2004b.
[3] Dodov, B., and E. Foufoula-Georgiou, Fluvial processes and streamflow variability: Interplay in the scale-frequency continuum and implications for scaling, *Water Resour. Res.*, 41, W05005, doi:10.1029 /2004WR003408, 2005.
[4] Gupta, V. K., O. J. Mesa, and D. Dawdy, Multiscaling theory of floods: Regional quantile analysis. *Water Resour. Res*., 30(12), pp. 3405-3421, 1994.
[5] Leopold, L. B. and T. Maddock, The hydraulic geometry of stream channels and some physiographic implications, *U.S Geol. Survey Prof. Paper*, 252, 57p., 1953.
[6] Noman, N. S., E. J. Nelson, and A. K. Zundel, A Review of Automated Flood Plain Delineation from Digital Terrain Models, *ASCE Journal of Water Resources Planning and Management*, Vol. 127, No. 6, pp. 394-402, 2001.
[7] Prasad, L., Morphological Analysis of Shapes, *CNLS Newsletter*, No. 139, LALP-97-010-139, Center for Nonlinear Studies, T-DOT, Theoretical Division, Los Alamos National Laboratory, 1997.
[8] Smith, J. A., Representation of basin scale in flood peak distributions, *Water Resour. Res.*, 28(11), pp. 993-2999, 1992.

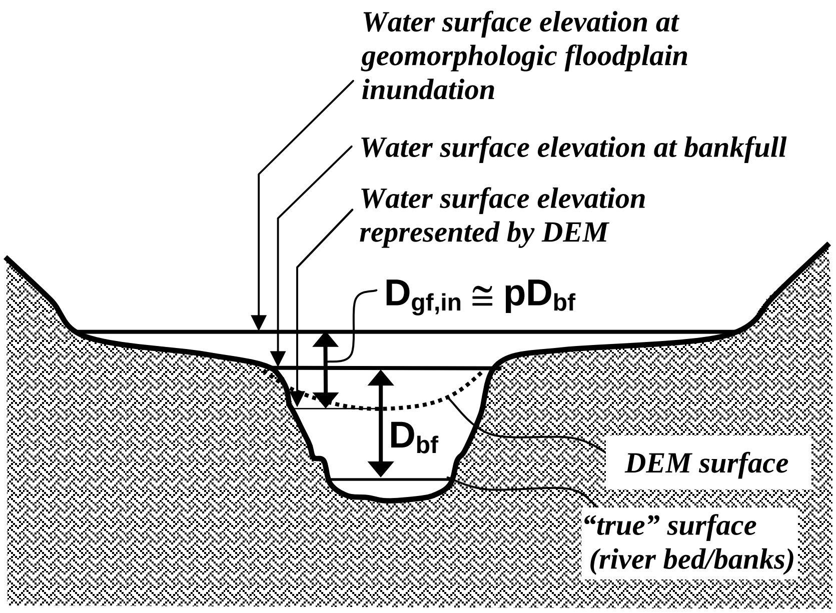

Fig. 1. Definition of bankfull depth (D_{bf}) and geomorphologic floodplain (GF) inundation depth ($D_{gf,in}$) (modified from Fig. 18 of [3]). Note the different datum of these depths: D_{bf} is relative to the true river bed surface (not detectable in a DEM), whereas $D_{gf,in}$ is relative to the DEM surface. The proportionality constant p is derived empirically.

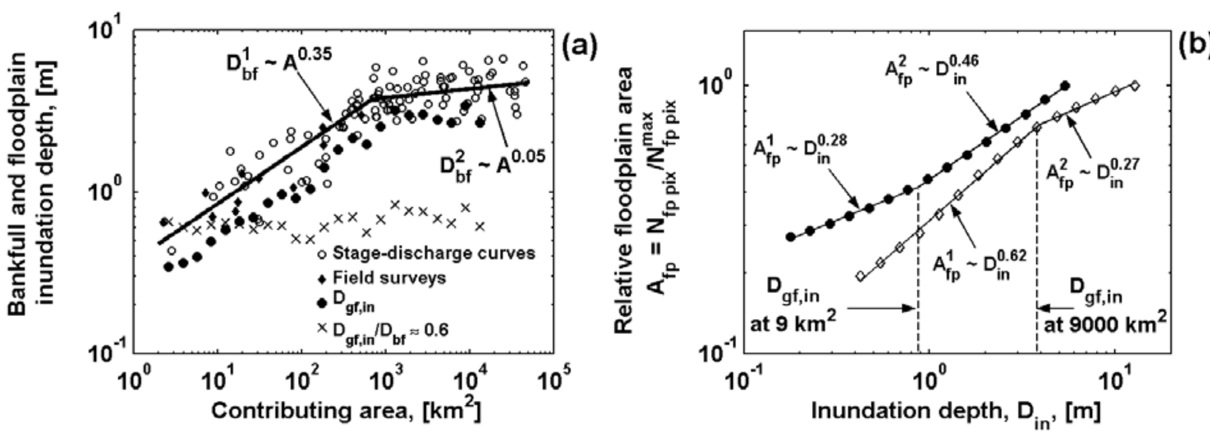

Fig. 2. Fig. 2. (a) Bankfull depth D_{bf} (open circles) versus contributing area for 113 stations (computed from stage-discharge curves or field surveys) and GF inundation depth $D_{gf,in}$ (solid circles) estimated with the process of Fig. 1 for the Neosho River basin; (b) Determination of the GF inundation depth $D_{gf,in}$ shown for two scale intervals centered at 9 and 9,000 km^2. It is noted from Fig. 2a that the ratio of $D_{gf,in}/D_{bf}$ is constant and approximately equal to 0.6.

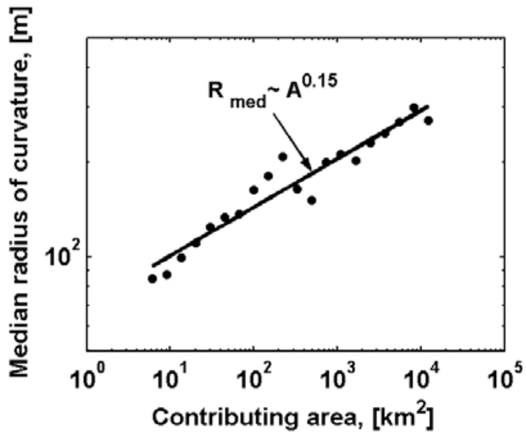

Fig. 3. Median radius of curvature vs. contributing area based on the analysis of the high resolution hydrography data of the Neosho River basin.

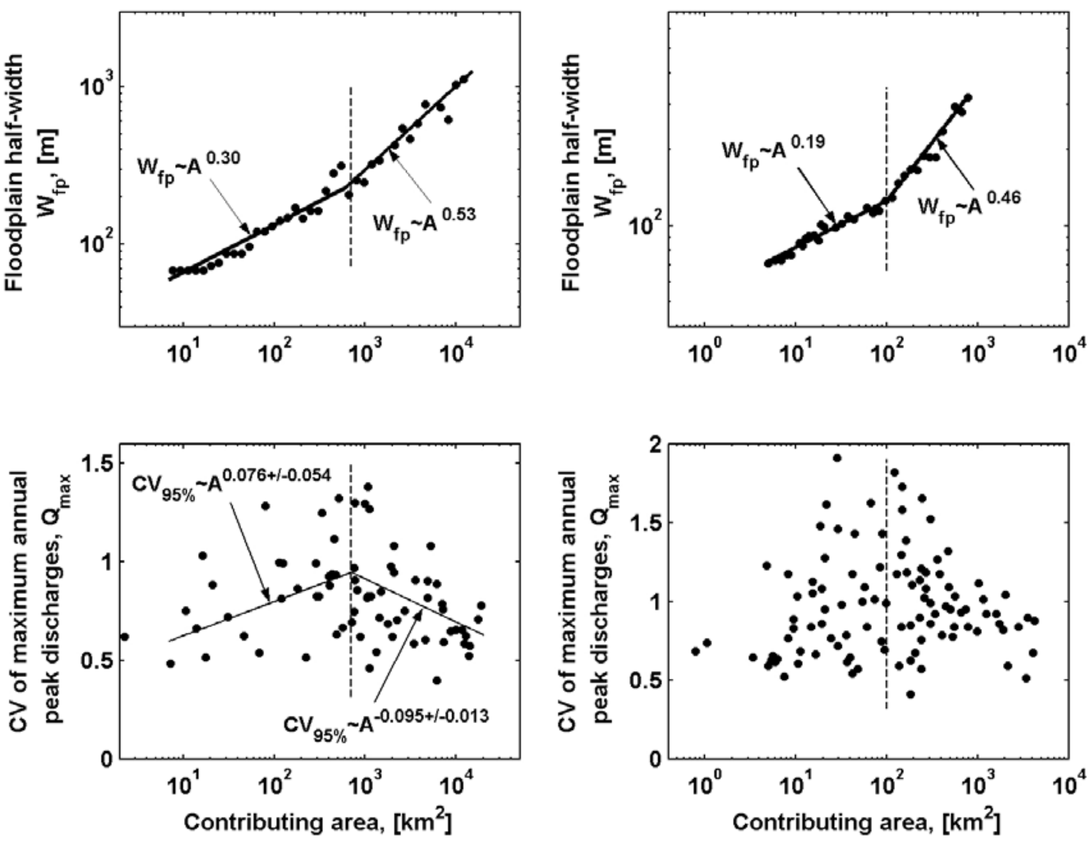

Fig. 4. *Top plots*: Floodplain half-width versus scale (contributing area) for the Neosho River basin (left) and a basin in the Appalachian highlands (right). *Bottom plots*: coefficient of variation (CV) of maximum annual peak discharges versus scale for 72 stations in Oklahoma-Kansas (left) and the 104 stations of Smith, 1992 [8] (right).