Environmental Hydraulics – Christodoulou & Stamou (eds)
© 2010 Taylor & Francis Group, London, ISBN 978-0-415-58475-3

On the use of Digital Surface Models and hydrological/hydraulic models for inundated area delineation

I. Leventi & I. Nalbantis
Laboratory of Water Reclamation Works and Water Resources Management, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece

A. Georgopoulos
Laboratory of Photogrammetry, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT: Critical issues are investigated regarding the use of Digital Surface Models (DSMs) in flood hazard modelling and assessment. These concern the necessary methodological steps to exploit DSMs for delineating inundated areas as well as the DSM accuracy required. The methodology proposed is comprised of a typical photogrammetric procedure to produce DSM combined with typical hydrological and hydraulic models. The design flood approach is followed in hydrological modelling using the SCS method coupled with a Unit Hydrograph. Hydraulic quantities such as water depth and velocity are assessed through numerically solving the full one-dimensional Saint-Venant equations for unsteady flow conditions in open channels. Application to Rapentosa basin, Eastern Attica, Greece allows useful conclusions regarding the use of DSMs produced via photogrammetry and the effect of DSM accuracy on inundated area delineation.

1 INTRODUCTION

To mitigate the impact of flooding a variety of measures, whether constructive or non-constructive, are implemented. In the design phase of such measures the use of hydrological and hydraulic models is nowadays generalized. These models yield estimates or predictions of the flood hazard in terms of hydraulic quantities such as water depth and velocity. They require topographical information at a variety of scales: conventional maps of scale from 1:50000 down to 1:5000 for hydrological modelling and more detailed maps from 1:5000 down to field surveys scales for hydraulic modelling.

Modern technology which is based on Digital Surface Models (DSMs) is currently widely exploited in hydrological research while in hydraulic research the use of DSMs is less extended, especially for assessing flood hazard. Far less common is the widespread use of DSMs in engineering practice. Currently, the existing body of knowledge does not allow for establishing general guidelines on using DSMs in flood hazard assessments. This is due to two reasons: (1) the difficulty in processing DSM-based topographical information within existing hydrological and hydraulic models, and (2) the lack of knowledge on the required DSM accuracy. Efforts to exploit information from DSMs can be traced back to 1990s (Cabral et al. 1990; Garotte & Bras 1995) while very few commercial software packages have only recently adapted to using DSM data. A typical example is the HEC-RAS package (USACE 2003). Although knowledge on DSM production methods and the related accuracy is relatively well established (Maune 2007; Li et al. 2005) some questions regarding the use of DSMs in hydrology remain open. These refer to: (1) the effect of various parameters related to sensors used for raw data collection; (2) the effect of parameters of the method used for DSM production; (3) the effect of procedure used to extract information of hydrological interest (e.g. basin morphometric characteristics). The research in relation to hydrological modelling is limited (Brasington & Richards 1998; Valeo & Moin 2000; Chaubey et al. 2005). The same holds for hydraulic modelling (Marks & Bates 2000; Werner 2001; Vazquez et al. 2002; Tate et al. 2002; Bates et al. 2003; Omer et al. 2003; Wang & Zheng 2005).

This study constitutes a contribution to enhancing knowledge in using DSMs which are produced through photogrammetric methods. It addresses two critical questions: (1) What are the necessary methodological steps to exploit DSMs in flood hazard assessments? (2) What is the required accuracy of DSM to accurately delineate inundated areas?

2 METHODOLOGY

2.1 *General*

A methodology for flood hazard assessment is proposed and tested which is comprised of: (1) a typical photogrammetric procedure to produce DSM, (2) a typical hydrological modelling approach, and (3) a typical hydraulic model. The study basin is separated in two parts: (1) the upper sub-basin which produces most of the runoff generated during flood events; (2) the lower sub-basin, usually of lower spatial extent, which receives runoff from the upper sub-basin and is subject to flooding; this is the only area for which "flood hazard" is evaluated since it is there that flood severely threatens human lives, infrastructures and the environment. The upper sub-basin is modelled through hydrological models which provide output flood hydrographs while, for the lower sub-basin, hydraulic models are used which yield the necessary output information. Models and procedures are described next.

2.2 *Photogrammetric procedure*

The photogrammetric procedure selected consists of the following: (1) collection of aerial photos; (2) measurements for ground control points with the aid of GPS; (3) application of an aerotriangulation procedure for the orientation of aerial photos; this is carried out on digitized aerial photos produced via scanning; (4) production of DSM; (5) production of the orthophoto of the study area which is useful in having a better view and control of information used later in hydrological and hydraulic modelling.

2.3 *Hydrological modelling*

Hydrological modelling is based on the design flood approach and is comprised of five steps. In Step 1 frequency analysis is carried out on a sample of annual maximum rainfall intensity from a raingauge in the study basin or within the wider region. By adopting the Generalised Extreme Value (GEV) distribution a generalised intensity-duration-frequency (idf) curve is obtained (Koutsoyiannis et al. 1998) which has the form

$$i = \frac{\lambda\psi + \dfrac{\lambda}{\kappa}\left[\left(-\ln\left(1-\dfrac{1}{T}\right)\right)^{-\kappa} - 1\right]}{(d+\theta)^{\eta}} \tag{1}$$

where i = annual maximum rainfall intensity for return period T and rainfall duration d; λ, ψ, η, θ = parameters. The methodology proposed by Koutsoyiannis et al. (1998) is used for parameter estimation.

In Step 2, design storm hyetographs for selected return periods ($T = 5$, 10, 50, 100, 1000 and 10000) are constructed assuming total storm duration and distributing total rainfall depth with the aid of the alternating block method.

In Step 3 rainfall excess hyetographs are computed which are related to the above storm hyetographs. For this the well-known SCS method is used which yields excess rainfall depth P_e as

$$P_{\mathrm{e}} = \begin{cases} \dfrac{(P - I_{\mathrm{a}})^2}{P - I_{\mathrm{a}} + S} & P > I_{\mathrm{a}} \\ 0 & P \le I_{\mathrm{a}} \end{cases} \tag{2}$$

where P = cumulative rainfall depth from the storm beginning; S = potential maximum retention, and I_a = initial abstractions before ponding, usually taken equal to $0.2S$. Quantity S is related

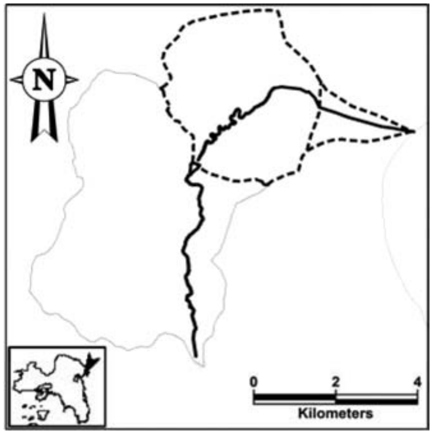

Figure 1. The Rapentosa Basin and its main water course (thick continuous line); sub-basin boundaries are in thin continuous line for the upper sub-bassin (upstream of the dam) and in thick dashed line for the lower sub-basin (downstream of the dam); the unmodelled (most downstream) part of the latter (to the right) is separated with thick dashed line from the modelled part.

to a dimensionless parameter known as the curve number and denoted as CN. In SI units this relationship is

$$S = 254\left(\frac{100}{\mathrm{CN}} - 1\right) \tag{3}$$

where S is given in mm.

Steps 4 and 5 are respectively devoted to constructing the basin's synthetic Unit Hydrograph and obtaining the hydrographs of direct runoff which are related to the excess rainfall hyetographs constructed in Step 3. No baseflow is considered which is insignificant for watercourses with torrential flow such as the one studied in this work.

Finally, the design hydrograph is routed through the reservoir which is, in some cases, located at the outlet of the upper sub-basin. For this the level-pool method is used.

2.4 *Hydraulic modelling*

The full one-dimensional Saint-Venant equations are numerically solved for unsteady flow in open channels. For this the DAMBRK package is used. The outflow hydrograph of the upper sub-basin forms the boundary condition at the most upstream section considered. The floodplain geometry is described through coordinates at a number of valley sections across the central flow path for high flows. The following quantities are obtained on output: water depth, section-averaged water velocity, and discharge as functions of time (in a discrete sense) and space (for discrete sections). The extent of the inundated area corresponding to maximum water depths throughout the whole flood event is considered as the flood hazard estimate.

3 APPLICATION AND RESULTS

3.1 *The study basin*

The above methodology is applied on a river basin located within the wider area of Marathon and more specifically in Rapentosa, Eastern Attica, Greece (Fig. 1). The upper sub-basin is considered upstream of the existing dam and the lower sub-basin downstream of that dam. The basin's land uses are pasture, forests, cultivated and residential areas. The basin's main morphometric characteristics are depicted in Table 1. As to geological formations, the region is comprised of marble, schist and quaternary sediments. At the outlet of the upper sub-basin a dam has been constructed which serves floodwater detention. The main characteristics of this dam are given in Table 2.

Table 1. Morphometric characteristics of the Rapentosa basin.

Characteristic	Value
Total basin area (km^2)	37.4
Area of upper sub-basin (km^2)	23.2
Area of lower sub-basin (km^2)	14.2
Main course length for upper sub-basin (km)	5.85
Total main course length (km)	10.58
Mean elevation of total basin (m a.m.s.l.)	447.1
Maximum elevation of upper sub-basin (m a.m.s.l.)	1090.0
Minimum elevation of upper sub-basin (m a.m.s.l.)	160.0
Minimum elevation of lower sub-basin (m a.m.s.l.)	0.0

a.m.s.l. means above mean sea level

Table 2. Characteristics of the Rapentosa Dam and of the related reservoir (Sioras, 2006).

Characteristic	Value
Dam height (m)	38.0
Reservoir storage capacity (106 m^3)	1.25
Elevation of dam crest (m a.m.s.l.)	174.5
Length of dam crest (m)	120.0
Elevation of spillway crest (m a.m.s.l.)	170.5
Length of spillway crest (m)	20.0
Elevation of evacuation conduit (m a.m.s.l.)	154.0
Diameter of evacuation conduit (mm)	700.0
Conveyance capacity of evacuation conduit (m^3/s)	6.0

3.2 *The DSM of the basin*

The analyses were based on a DSM which was previously produced within the frame of DISMA project (Tsakiris et al. 2007). The data collection campaign took place in September 2005 and main characteristics of the DSM production process are depicted in Table 3. More details are given by Leventi (2008). This DSM is of accuracy about one meter when accuracy is expressed as the 95% confidence interval of elevations. In our tests it will be termed as the high-accuracy DSM. For testing purposes it was contaminated with random errors so as to obtain a low-accuracy DSM having an accuracy of about 3 m.

3.3 *Results*

To test the sensitivity of the flood hazard estimate in regard to the DSM accuracy, the original or high-accuracy DSM is contaminated with random errors of known statistical properties. Comparing results from the two DSMs helps quantifying the sensitivity mentioned above. For this we use the mean horizontal distance of inundated area boundaries in cross-sections along the main water path for the 50-year-return-period flood tested. Other statistics of this quantity are shown in Table 4. In Figure 2 are depicted the outflow of the upper sub-basin which ism at the same time, the inflow to the Rapentosa Reservoir; also, the reservoir outflow hydrograph is shown in the same figure. The inundated area boundaries for the two DSMs are shown in Figure 3.

4 CONCLUSIONS

The main conclusions drawn from this work are the following:

– The use of DSMs and orthophotos in flood hazard assessments allows for obtaining very useful information regarding the relief and land uses in flood-prone areas without resorting to surveying campaigns.

Table 3. Main characteristics and parameters of the DSM production process for the study basin (Tsakiris et al. 2007).

Characteristic	Value
Number of aerial photos	14
Number of stereo-pairs	11
Number of ground control points	10
Standard error after aero-triangulation (m)	
x coordinates	0.18
y coordinates	0.22
z coordinates (elevations)	0.22
Total number of stereo-model points	740000
Total number of points in TIN	148000
DSM grid spacing (m)	30

Table 4. Statistics of horizontal distance of inundated area boundaries in cross-sections along the main water path.

Statistic	Value (m)
Mean	17.8
Standard deviation	12.4
Maximum	48.0

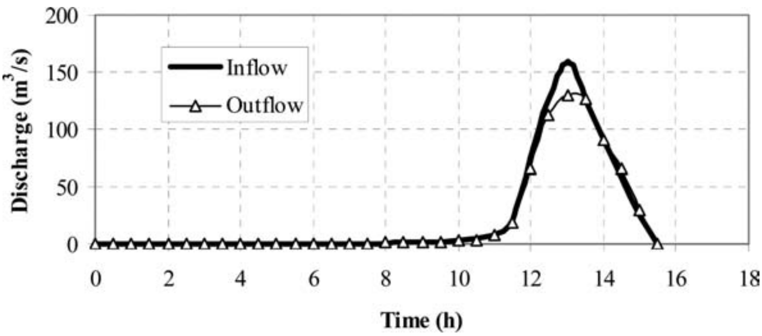

Figure 2. Inflow and outflow hydrographs for Rapentosa Reservoir and the 50-year return period.

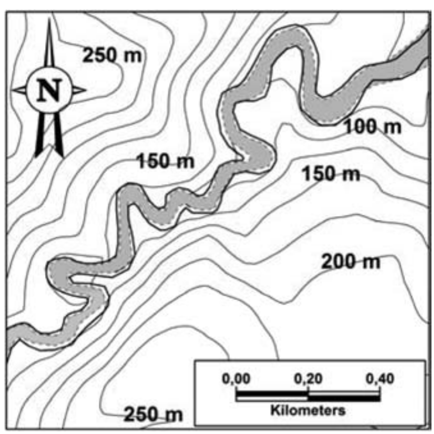

Figure 3. Layout of inundated area for the 50-year-return-period flood for the case with high-accuracy DSM (area in grey) and the case with low-accuracy DSM (thick line).

– In general, the above information fulfils data requirements for hydrological and hydraulic models used in this kind of studies.
– Extracting any extra information during the modelling process is very easy and allows for avoiding new in-situ measurements thus speeding up the modelling process.
– The proposed methodology involves higher costs as compared to the conventional use of maps and surveys, mainly due to DSM production costs; yet, it can become economically attractive if one takes into account that DSMs very often serve multiple purposes to which significant parts of the total production cost can be allocated.
– Sensitivity tests showed that in some cases a DSM of low accuracy can be sufficient for inundation area delineation; this conclusion is, however, provisional and requires further tests.

REFERENCES

Cabral, M. C., Bras, R. L., Tarboton, D. & Entekhabi, D. 1990. A distributed, physically-based, rainfall runoff model incorporating topography for real-time flood forecasting. *Ralph M. Parsons Lab. Rep. N. 332*. Cambridge, MA: MIT Department of Civil Engineering.

Garrote, L. & Bras, R. L. 1995. A distributed model for real-time flood forecasting using digital elevation models. *Journal of Hydrology* 167: 279–306.

Bates, P. D., Marks, K. J. & Horritt, M. S. 2003. Optimal use of high-resolution topographic data in flood inundation models. *Hydrolog. Process.* 17(3): 537–557.

Brasington, J. & Richards, K. 1998. Interactions between model predictions, parameters and DTM scales for top model. *Comput. Geosci.* 24(4): 299–314.

Chaubey, I., Cotter, A. S., Costello, T. A. & Soerens, T. S. 2005. Effect of DEM data resolution on SWAT output uncertainty. *Hydrolog. Process.* 19(3): 621–628.

Koutsoyiannis, D., Kozonis, D. & Manetas, A. 1998. A mathematical framework for studying rainfall intensity-duration-frequency relationships. *Journal of Hydrology* 206: 118–135.

Leventi, I. 2008. *Assessing flood hazard based on Digital Surface Models.* Diploma thesis. Athens: School of Rural & Surveying Engineering, National Technical University of Athens (in Greek).

Li, Z., Zhu, Q. & Gold, C. 2005. *Digital Terrain Modeling: Pronciples and Methodology*. ISBN 0-415-32462-9, 323 pp., CRC Press.

Marks, K. & Bates, P. 2000. Integration of high-resolution topographic data with floodplain flow models. *Hydrolog. Process*. 14(11–12): 2109–2122.

Maune, D.F. (ed.) 2007. *Digital Elevation Model Technologies and Applications.* 2nd ed, 620pp. ASPRS editions.

Omer, C. R., Nelson, E. J. & Zundel, A. K. 2004. Impact of varied data resolution on hydraulic modeling and flood plain delineation. *J. Am. Water Resour. Assoc.* 39(2): 467–475.

Sioras, P. 2006. Characteristics of the Rapentosa Dam, Personal communication. Athens.

Tate, E. C., Olivera, F. & Maidment, D. R. 2002. Creating a terrain model for floodplain mapping. *ASCE J. Hydrol. Eng*. 7(2): 100–108.

Tsakiris, G., Pistrika, Aim., Klampanos, I., Laoupi, A., Ioannidis, Ch., Soile, S. & Georgopoulos, A. 2007. DISMA-Disaster Management GIS with emphasis on cultural sites – Technical Report – Volume I (unpublished). INTERREG IIIC – Sud Initiative and the Regional Operation Framework of NOE Programme – Patrimoine et prevention des risques naturels. Athens, Greece: Centre for the Assessment of Natural Hazards and Proactive Planning.

USACE [US Army Corps of Engineers] 2003. *HEC-GeoRAS Version 3.1.1*. Davis, CA: Institute for Water Resources, Hydrologic Engineering Center.

Valeo, C. & Moin, S. M. A. 2000. Grid-resolution effects on a model for integrating urban and rural areas. *Hydrolog. Process.* 14(14): 2505–2525.

Vazquez, R. F., Feyen, L., Feyen, J., & Refsgaard, J. C. 2002. Effect of grid size on effective parameters and model performance of the MIKE-SHE code. *Hydrolog. Process.* 16(2): 355–372.

Wang, Y. & Zheng, T. 2005. Comparison of digital elevation models and understanding of their impact on the flood extent mapping on a coastal floodplain of North Carolina. *Nat. Hazards Rev.* 6(1): 34–40.

Werner, M. J. F. 2001. Impact of grid size in GIS based flood extent mapping using a 1D flow model. *Phys. Chem. Earth,* Part B, 26(7–8): 517–522.