Science in China Series E: Technological Sciences
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Flood inundation extent in storage cell mode

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An understanding of floodplain processes in general and floodplains flooding in particular are vital issues for river engineers and managers. Insufficient observations of flood inundation extent and the infrequent nature of flood inundation necessitate some sort of predictive tools. In this paper flood inundation extent has been simulated by HEC-RAS software in two storage cell and normal modes and capabilities and limitations of the two models have been determined by comparing simulated and observed flood inundation extent occurred in the study area in Feb 4th, 2004.

Keywords: flood, 1-D models, HEC-RAS-Storage cell model

1 Introduction

Nowadays, flood inundation extent is taken into account as a major natural hazard in world-wide and its prediction is a significant task for planners, environmental managers and the insurance industry.

Regarding insufficient information and observed data from inundation extents which occur for most rivers and also infrequent nature of flood occurrence, the need of some models to predict flood inundation extent are essential. The most common and conventional models to simulate fluvial flows in general and flood inundation extent in particular are 1-dimensional models based on St Venant equations, solved using numerical solution techniques[1,2]. Examples of these models are known as MIKE 11, HEC-RAS, FLUCOMP, ONDA and ISIS. Some of the advantages of these models are that they are applicable and also are well suited to parameterization using traditional field surveying methods. There are some issues concerning these models that rises from assumptions made to the equations used, including the one dimensionality of the flow, uniformity of velocity and horizontally of water level across the cross-sections [3]. Although it has been well acknowledged that in-channel flows may be satisfactorily described by a 1D representation, but for modeling floodplain flows for floodplain with complex topography, they can cause problems [4]. To overcome these limitations, two-dimensional finite difference and finite element models based on Navier-Stocks equations have increasingly been developed and applied [5,6-7]. Process representation in these models is a logical development of one-dimensional approaches as in the model process representation they include lateral shear, secondary flows and turbulence which in 1-dimensional model are defined as a one function named roughness coefficient[5]. Some of 2-D model that can be introduced are Hydro 2D, RMA2 and TELEMAC. These models also contain limitations including increased computational cost and less suitability to parameterization using traditional cross section surveys [8,9,10]. As yet, no consensus exists concerning the level of model process complexity required to achieve satisfactory prediction in terms of flood inundation extent [5]. As one-dimensional approximation of in-channel flow is broadly accepted [11,12], the question of optimum level of flow process complexity for floodplain flows in relation to inundation extent predictions is still open. Due to limitations of 1-2 dimensional models there have been some proposed models which can be known as quasi two-dimensional models [5]. Although the two-dimensional

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Received July 10, 2009; accepted August 4, 2009
doi: 10.1007/s11431-009-0371-2

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Citation: Farahi G, Khodashenas S R, Ghahraman B, et al. Flood inundation extent in storage cell mode. Sci China Ser E-Tech Sci, 2009, 52(11): 1-6, doi: 10.1007/s11431-009-0371-2

unsteady flow equations are not used to explain the flow behavior on the floodplain, the physical situation in which channel and floodplain form a two-dimensional network for flow movement is perfectly simulated. One of these models that can be introduced is HEC-RAS in storage cell mode.

In this method floodplain can be represented as series of storage cells hydraulically connected to the main channel and themselves. This method will be aggravated on floodplains with either natural obstacles or man-made structures (dykes, elevated roads field walls, embankments etc.). In such cases, the land surrounding the main channel (i.e., floodplain) may comprise a series of discrete areas acting as storage cells, which hydraulically communicate with their neighbors and/or the main channel[5,13–14] (Figure 1). The topographic features of the floodplain under study in this research (i.e., the presence of stone walls that cross the floodplain as a series of discrete storage cells) suggest a storage cell approach might be appropriate. Thus, a network of interconnected storage cells for routing floodplain flows is used to predict flood inundation extent. Data was also used to predict flood inundation extent by HEC-RAS in normal mode.

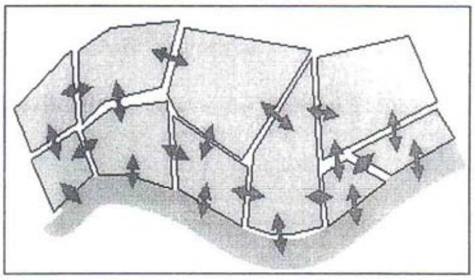

Figure 1 Schematic form of interconnected storage cells on the floodplain.

This paper intends to study the ability of predicting flood inundation extent in HEC-RAS in normal mode (a conventional model) and HEC-RAS in storage cell mode by comparing the maximum predicted inundation extent with observed inundation extent for a flood extent occurred over the study reach on Feb 4th, 2004.

2 Materials and method

2.1 Study area

The test site in this study is based upon a 6 km upper reach of the River Wharf, UK (Figure 2). This comprises a typical upland gravel-bed river with a range of 10 to 15 meter in width. It is generally single thread, with individual meander bend series linked by relatively 5 straight tributaries. The floodplain is relatively wide compared with the river width and has a slope of approximately 0.0040 and is divided by a mixture of dry-stone walls, hedges and fences. Observations suggest that the dry-stone walls are largely impervious to flow, except where there are gates, and exert an important control on flood routing.

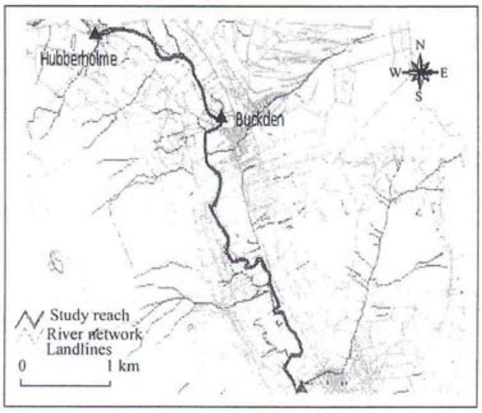

Figure 2 The study reach in Upper Wharf, UK.

2.2 Prediction of flood inundation extent by HEC-RAS in storage cell mode

As previously mentioned, there are some limitations using conventional 1-D models to predict flood inundation extent, which rises from assumptions made to simplify governing equations. In response, HEC-RAS in storage cell mode can be an ultimate method to overcome these limitations. This approach can demonstrate the floodplain much better than the conventional one-dimensional models. Unlike one-dimensional models, in this method, the flow direction on the floodplain is considered to be independent of the flow direction of main channels and also water surface elevations in the main channel and on the floodplain can also be different. In this approach, once the river overtops, the floodplain is inundated in a manner dictated by local topography at each cell, at least at the beginning of inundation and then hydraulic connectivity between storage cells controls flood inundation extent on the floodplain. Although the two-dimensional unsteady flow equations are not used to explain the flow behavior on the floodplain in this method the physical situation in which channel and storage cells form a two-dimensional network for flow movement is perfectly simulated.

The data needed to predict flood inundation extent in storage cell mode are divided in two groups: (i) Geometric data and (ii) Unsteady hydraulic data. Geometry data include river morphology, cross sections data, design and parameterization of storage cells, position and dimension of hydraulic connections between storage cells and/or river, energy losses coefficient (roughness coefficient, expansion and contraction coefficient) and location and dimension of hydraulic structures (bridge, weir and etc.). Unsteady flow data include initial and boundary conditions of the hydraulic model.

Topography of the study reach of river wharf catchment was available as in grids and also the location of river, roads, fences and etc. were also available as Land line, in which they were all defined in ArcGIS. To determine the exact shape of river and location of each cross-section an extension of ARCGIS called HEC-GeoRAS was developed to process geospatial data for use in HEC-RAS. It means that HEC-GeoRAS which includes determining (i) river centre line (ii) river banks (iii) flow direction, and (iv) cross sections, in ArcGIS software, creates an import file for HEC-RAS that contains most of the necessary geometric data, and displays the river system in HEC-RAS in a real-world coordinate system. After exporting information from ArcGIS to HEC-RAS, dimensions of each cross-section was then corrected with the exact data provided by surveying techniques such as leveling and GPS. In this case, unlike the conventional one-dimension models, cross-sections are only extended to the river bank. The next step was to determine the river and floodplain Manning *n* as part as energy loss coefficients. The river and floodplain manning *n* were defined separately depending on their physical conditions such as surface roughness, vegetation, channel irregularities, etc. by using HEC-RAS manning's *n* table. The assumed Manning *n* for river and floodplain (from the observations) were 0.04–0.06 and 0.06 respectively. In the next step boundary and initial conditions were entered. Boundary conditions had to be established for downstream and upstream ends of the river system. For upstream end of the main river, inflow hydrographs of the flood accrued on Feb 4th 2004 and for downstream normal depth were used. In HEC-RAS, to describe normal depth the energy line slope has to be entered, so the software will calculate the normal depth by using Manning's equation. When applying normal depth as a downstream boundary condition, it should be placed far enough downstream, so that its effects will not influence model calculations at the downstream part of the model. The friction slope was set within the range of 0.001–0.005, same as river bed slope [15]. The main river in the catchment had five tributaries. For boundary conditions observed inflow hydrograph from the tributaries to the main channel for flood event accrued on 4th Feb 2004 was used. Initial conditions consist of stage and flow data at all existing cross-sections, in this case initial discharge of the observed hydrograph (1.9 m^3/s) was used. Initial condition at each storage cell was set as minimum ground level of each storage cell plus minimal flood flow depth.

2.3 Storage cells design and parameterization

One of the options of geometry data in HEC-RAS is to specify the location of each storage cell on the floodplain. This can be done by the use of existing Ordnance Survey (OS) Landline data which defines roads, fields, and fences. These data were also used to identify dimension and location of their hydraulic connections to the neighboring cells and/or the main channel. In some cases, cells had to be joined together to make a single cell. One of the limitations of HEC-RAS in designing storage cells is that a cell cannot have more than 8 hydraulic connections [15]. In this state, hydraulic connections were set across the cell boundaries. A total of 61 storage cells were finally designed for the floodplain in this reach. By using LiDAR data, elevation-volume relation of each storage cell was defined as part of geometry data. The next step was to determine the location of each hydraulic connection. There were two kinds of hydraulic connections, the hydraulic connections between storage cells and connections between storage cells and the main channel. Hydraulic connections between storage cells were presented using weirs and between storage areas and the main channel by using lateral weirs. HEC-RAS software uses lateral weir and weir equations to transport water from river to and along the floodplain.

3 Calibration

Before calibrating the models parameters, the sensitivity of the model prediction upon uncertain parameters was studied. In this research, scenarios based upon changes of Manning's n and normal depth as a boundary condition were selected for sensitivity analysis.

The results showed that the main channel friction factor and normal depth have a considerable impact on model predictions. Since there is no flux in the floodplain, changes of the Manning's n has no actual role on models prediction. Since $Sf = f(n)$, first we determined the river roughness and then the friction slope.

4 Determining the rivers roughness coefficient

In the first step, floodplain Manning's n and friction slope remained constant at 0.06 and 0.0005 respectively. The channel friction changed from a starting value of 0.04 and increased in increments of 0.005 up to a maximum value of 0.06. For each scenario maximum water level compared with maximum observed water level for flood event occurred on the Feb 4th, 2004.

To ascertain the best roughness coefficient, for each scenario average error of the below equations was obtained. The Manning's n with minimum average error was chosen as the optimum river roughness coefficient for this particular flood event (Table 1).

$$\mathrm{Err}_m = \frac{1}{n}\sum\left|\frac{(x_i - x_m)}{x_m}\right|, \qquad (1)$$

$$\mathrm{RMSE} = \frac{1}{n}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - x_m}{x_m}\right)^2}, \qquad (2)$$

where x_i is the simulated water level for cross-section i and x_m is the observed water level for the same cross section and n is the number of cross sections. Table 1 shows that the minimum error is obtained using an n value of 0.05.

Table 1 Predicted water level in specified cross-sections

istance from downstream end (m)	Observed water level (m)	Predicted water level (m)			
		n=0.045	n =0.05	n=0.055	n=0.06
4357	226.1	226.16	226.23	226.29	226.34
4263	225.8	225.72	225.74	225.77	225.79
4120	225	224.96	224.98	225	225.01
3528	222.76	222.29	222.37	222.45	222.51
3324	221.89	221.47	221.54	221.59	221.63
2918	220.09	219.8	219.86	219.91	219.94
2179	218.25	218	218.01	218.02	218.03
1821	217.55	217.16	217.18	217.2	217.21

5 Determining optimum friction slope

In the next step of calibration, the Manning's n of river and floodplain remained constant at 0.05 and 0.06 respectively and the value of friction slope varied between 0.0005-0.01. For each scenario, the maximum simulated water level was calculated and the results were compared with the maximum observed water levels (flood event occurred on Feb, 2004). The results showed that the effect of the model boundary condition in the downstream of the river is only limited on 1700 meter from the end of the model. Figure 4 shows that the maximum predicted water level obtained by the value of 0.0005 as a friction slope, fits best with the observed water level regarding other values of friction slopes.

6 Flood inundation extent prediction in HEC-RAS in normal mode

Data needed to run HEC-RAS in normal mode is completely the same as the storage cell mode, except in the normal mode there is no need for storage cell and hydraulic connections data whereas cross sections must be extended across entire floodplain.

1470	216.6	216.79	216.86	216.91	216.97
1086	216.15	216.13	216.2	216.26	216.32
585	215.8	215.78	215.92	216.05	216.18
44	215.55	215.46	215.61	215.77	215.92
Err_m (%)		0.105	0.094	0.1	0.106
RMSE (%)		0.133	0.12	0.12	0.123

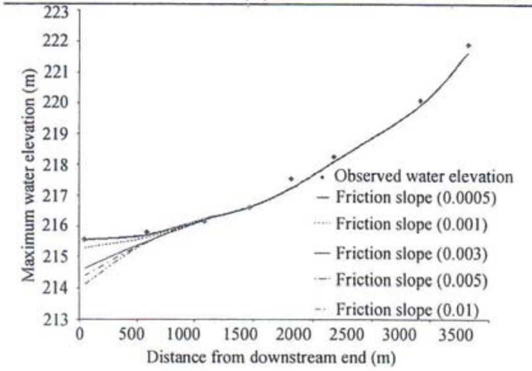

Figure 4 Maximum predicted water level using different friction slope values.

7 Validation

In order to find the maximum water level for each cross-section, by finding the best friction slope (0.0005) and river manning's *n* (0.05), HEC-RAS was run in normal and storage cell modes. The maximum predicted water level at each cross-section was then converted to flood inundation extent in ArcGIS by using HEC-geoRAS in the secondary processing step (Figures 5 (a) and (b)).

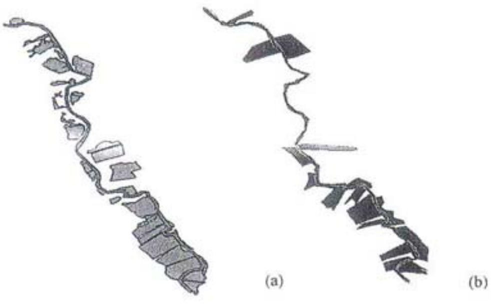

Figure 5 Comparison of inundation extent derived from (a) storage cell mode and (b) normal mode at their best calibration.

To predict inundation extent over the floodplain using storage cells mode, it was necessary to first map flow distributions over each storage cell at the peak water level. To do that, the peak water level at each storage cell was extracted so pixels that had levels less than maximum water level were considered as flooded areas. By merging separate inundation extents for each storage cell, the inundation extent for the entire floodplain was created. For validating the models the observed inundation map for flood event which occurred in the study reach on Feb 4th, 2004 was then compared with the predicated inundation extents in normal and storage cell modes by using an accuracy assessment called kappa analysis.

8 Conclusion

The result showed that the model performance in storage cell mode in relation to inundation extent was 64% whereas this figure was 49% in the case of normal mode. Similarity of storage cell mode in relation to flood inundation extent regarding observed inundation extent can be the result of considering floodplains topography and also defining connectivity between river and each storage cell along the river as hydraulic connections.

In order for floodplain to become flooded in both modes, the maximum water elevation of each cross-section must excides their banks elevation which in storage cell mode this has been defined as lateral weir crests. For flood event which occurred in 2004, maximum predicted water levels of most cross-sections were less than its banks elevation or lateral weir crest in the case of storage cell modes, so that for most of the rivers cross-section in normal and storage cell modes no current was conveyed from river to floodplain, but the advantage of storage cell mode over normal mode is that in this situation the water which has been conveyed into floodplain from any cross-section can be distributed over floodplain to the downstream by means of hydraulic connection between storage cells. Unlike storage cell mode, in normal mode the maximum inundation extent is obtained by merging the maximum water elevation of consecutive cross-sections, therefore this has been led to lesser inundation extent.

By the results obtained from both modes it can be concluded that one-dimensional models do not have the ability to predict flood inundation extent over floodplains with complex topography and this can be served as a massage which can lead us to use more complex hydraulic models with more than 1 dimension for this kind of floodplains.

Reference

1 Fread D L, Anderson M G, Burt T P. Channel Routing. Hydrological Forecasting. Chichester: John Wiley, 1984. 209

2 Fread D L. Flow Routing. Handbook of applied Hydrology. Anderson M G, Burt T P, eds. Handbook of Applied. New York. McGraw-Hill, 1993. 1−36

3 Bates P D, Anderson M G. A two-dimensional finite-element model for river flow inundation. Proceeding of the Royal Society of London A, 1993, 440: 481-491

4 Tayefi V. One and Two Dimensional Modeling of Upland Floodplain Flows in Response to Different Channel Configuration. Dissertation of Doctoral Degree. Leeds: Leeds University, 2005. chapter 2.

5 Anderson M G, Bates P D. Initial testing of a two-dimensional finite element model for floodplain inundation. Proceeding of the Royal Society of London A, 1994, 444: 149-159

6 Bates P D, Lane S N. Preface: High resolution flow modeling in hydrology and geomorphology. Hydrol Process, 1998, 12: 1129-1130

7 Stewart M D, Bates P D, Anderson M G, et al. Modeling floods in hydro logically complex lowland river reaches. J Hydrol, 1999, 223: 85-106

8 Bates P D, Anderson M G, Baird L, et al. Modeling floodplain flow with a two-dimensional finite element scheme. Earth Surf Process Landforms, 1992, 17: 575-588

9 Horritt M S, Bates P D. Effects of spatial resolution on a raster based model of flood flow. J Hydrol, 2001, 253: 239-249

10 Marks K, Bates P D. Integration of high-resolution topographic data with floodplain flow models. Hydrol Process, 2000, 14: 2109-2122

11 Knight D W, Shiono K. River Channel and Floodplain Hydraulics. In: Floodplain Processes. Chichester: John Wiley, 1996, chapter 5. 139-181

12 Cunge J A, Holly F M, Verwey A. Practical Aspects of Computational River Hydraulics. Pitman, London, 1980. 178

13 Zanobetti D, Lorgere H, Cunge J A, et al. Le modele mathematique du delta du Mekong. La Houille Blanche, 1968, 23: 32

14 Zanobetti D, Lorgere H, Preissmanm A, et al. Mekong Delat mathematical model program construction. J Waterways and Harbors Div, ASCE, 1970, 96: 143-159

15 US Army Crops of Engineers, Hydraulic Engineering Center. HEC-RAS, Hydraulic Reference Manual, Version 1.0. 121, 2001