EMPIRICAL INVESTIGATION OF THE INFLUENCE OF FLOODPLAIN ATTENUATION EFFECTS ON FLOOD FLOW

S Ahilan, J.J. O' Sullivan, and M. Bruen

Centre for Water Resources Research, School of Architecture, Landscape and Civil Engineering, University College Dublin.

ABSTRACT

This paper presents a simplex index that can account for floodplain attenuation effects in flood frequency analysis. The approach adopted involved generating flood hydrographs with varying flood peaks and durations and routing these through a generalised two-stage river reach using the HEC-RAS flood routing model. HEC-RAS is a 1-Dimensional link and node model developed by the US Army Corps of Engineers that produced downstream hydrographs for a variety of floodplain geometries and hydraulic resistances. Differences in flood peak between the upstream and simulated downstream hydrographs were expressed in terms of relative attenuation for a variety of geometrical and resistance parameters of the two stage channel. These parameters are known to influence the attenuation capacity of river channels. The index was developed through analysis of a multivariate regression model that included these parameters.

Key words: Flood frequency analysis, two-stage or compound channels, floodplain flow, river modelling, HEC-RAS, floodplain attenuation index.

INTRODUCTION

Flood flows in river channels in Ireland are commonly influenced by the effects of floodplain storage. This influence tends to be greater than that experienced in UK catchments and may, in part explain why many growth curves in Ireland are mildly graded. This has significance for statistical methods of flood estimation recommended in the Flood Studies Report (FSR) for Ireland. Methods include single site flood frequency analysis and regional flood frequency analysis, or the Index Flood Method. At single site flood frequency analysis, the practise is for observed flood frequency curves to be extrapolated to obtain magnitudes of higher return period flows. This technique involves fitting a probability distribution to a series of historical flow observations and allows the probabilities of the future occurrence of flood events to be estimated.

The Index Flood Method is generally carried out in two stages. The first stage involves an estimate of the index flood. For ungauged catchments, this is determined from equations developed from a multivariate regression model related to catchment descriptors that have a statistically important influence on the rainfall-runoff process. However, these equations do not include a parameter that accounts for floodplain effects. For gauged catchments where a historical record of good quality hydrometric data is available, the index flood is obtained from the annual maximum series. The second stage of the Index Flood Method uses a regional growth curve to extract a multiplier for this index flood to estimate floods of required return period.

Failure to include floodplain attenuation effects in either single site or regional flood frequency analysis will potentially result in errors in estimated peak flows. Floodplain attenuation effects are inherently included in single site or regional flood frequency estimation procedures that use Annual Maximum series, resulting in calculated flows that are potentially underestimated. This presents a problem when these flows are used as inputs in river models where the flows are further attenuated. Therefore, the ability to properly account for floodplain effects in the hydrological analysis of catchments is essential to unravel this 'double accounting' of floodplain attenuation, particularly in the context of the growing desire to combine hydrological and hydraulic models in a manner that provides a detailed and spatially coherent representation of flood risk. Furthermore, in the context of using groups of similar catchments or ‘pooling groups’ to determine growth factors that can be applied to index floods for estimating peak flows of required probabilities (return periods), data from floodplain-affected (FPA) areas has the capacity to contaminate growth curve estimates at non FPA sites.

The importance of floodplain effects and the need for their inclusion in flood estimation was recognised by the Technical Steering Group of the Irish Flood Studies Update (FSU) programme. The FSU will supersede the Flood Studies Report (NERC, 1975) in Ireland and comprises Research and Development to provide methodologies for flood estimation. The FSU is arranged in six Work-Groups. The central theme of Work-Group 3 is flood hydrograph analysis and Work-Package 3.3 of this work-group, on which this paper is based, is centred on flood attenuation studies. This paper presents a means of indexing these floodplain effects in flood estimation methodologies.

BACKGROUND

Dissatisfaction with the omission of parameters to account for floodplain attenuation effects in FSR catchment-descriptor models has existed since the issue was raised at the first conference on the Flood Studies Report (ICE, 1975) where DR. T.M. Prus-Chacinski commented on his surprise *at the omission of another important factor, the width of the flood valley, which affects the valley storage. …..the size of a river and its valley is the integral of all climatic and geophysical factors*. It is recognised that if floodplain effects are to be included in flood estimation procedures, a means of either indexing the effect or treating it separately needs to be derived. In each case, a simple effective method of identifying the floodplain effects needs to be developed. In order to investigate the floodplain effects in flood risk assessment studies, much effort has been focussed on detailed hydrological modelling for specific sites where particular flood defence schemes need to be implemented. But in general, complicated floodplain models are not suitable to model floodplain effects in natural rivers (McCartney and Naden, 1995). In addition to that, any data used to identify and index the floodplain effect should be easily obtainable from data sources such as digital terrain models (DTMs).

Flood routing procedures have been used to identify floodplain effects in previous studies. These may be classified as either hydrological or hydraulic (Choudhury *et al*., 2002). Hydrological methods use the principle of continuity and an empirical or assumed relationship between discharge and the temporary storage volumes of water during the flood period (Shaw, 1994). A typical example of a simple hydrological flood-routing technique used in natural channels is the Muskingum flood-routing method (Shaw, 1994). Hydraulic methods of routing involve the numerical solutions of either the convective diffusion equation or the one–dimensional Saint–Venant equation of gradually varied unsteady flow in open channels (Tewolde and Smithers, 2006). The factors that should be considered in selecting a method include the floodplain characteristics, channel slope, hydrograph characteristics, the overall flow network and the flow regime (sub critical or supercritical flow). The presence of backwater effects are also important.

APPROACH TO STUDY

The approach that is adopted in this study is similar to that of Mason (1992) and involved generating flood hydrographs with flood peaks and durations corresponding to specified return periods. These hydrographs were routed through a generalised river reach using the HEC-RAS flood routing model. HEC-RAS is a 1-Dimensional link and node model developed by the US Army Corps of Engineers that can solve the one-dimensional Saint-Venant equations of gradually varied unsteady flow. These equations are discretised using the finite difference method and solved using a four point implicit (box) method. . The Saint-Venant equations are:

$$\frac{\partial A}{\partial t} + \frac{\partial \phi Q}{\partial x_c} + \frac{\partial (1-\phi)Q}{\partial x_f} = 0$$ **Eqn. 1**

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x_c}\left(\frac{\phi^2 Q^2}{A_c}\right)+\frac{\partial}{\partial x_f}\left(\frac{(1-\phi)^2 Q^2}{A_f}\right)+gA_c\left(\frac{\partial z}{\partial x_c}+S_c\right)+gA_f\left(\frac{\partial z}{\partial x_f}+S_c\right)=0$$

Eqn. 2

where $\phi=\frac{K_c}{K_c+K_f}$, $K=\frac{A^{5/3}}{nP^{2/3}}$, $S_c=\frac{\phi^2 Q^2 n_c^2}{R_c^{4/3}A_c^2}$ and $S_f=\frac{(1-\phi)^2 Q^2 n_f^2}{R_f^{4/3}A_f^2}$

Within these equations, Q is the total flow down the reach, A_c and A_f are the cross sectional area of the flow in the main channel and floodplain, x_c and x_f are distances along the channel and floodplain (these may differ between cross sections to allow for channel sinuosity), P is the wetted perimeter, R is the hydraulic radius (A/P), n is the Manning's roughness value and S is the friction slope. The parameter ϕ specifies how flow is partitioned between the floodplain and channel and as shown is dependent on the conveyance in the main channel, K_c , and on the floodplain, K_f .

The generalised HEC-RAS river model produced downstream hydrographs for a variety of floodplain geometries and hydraulic resistances. Differences in flood peak between the upstream and simulated downstream hydrographs were expressed in terms of relative attenuation for a variety of geometrical and resistance parameters of the two stage channel that are known to influence the attenuation capacity of river channels.

In this study, the generalised river reach shown in Figure 1 is based on average geometrical and resistance properties of the River Suir, Co. Tipperary, between Newbridge and Caher Park.

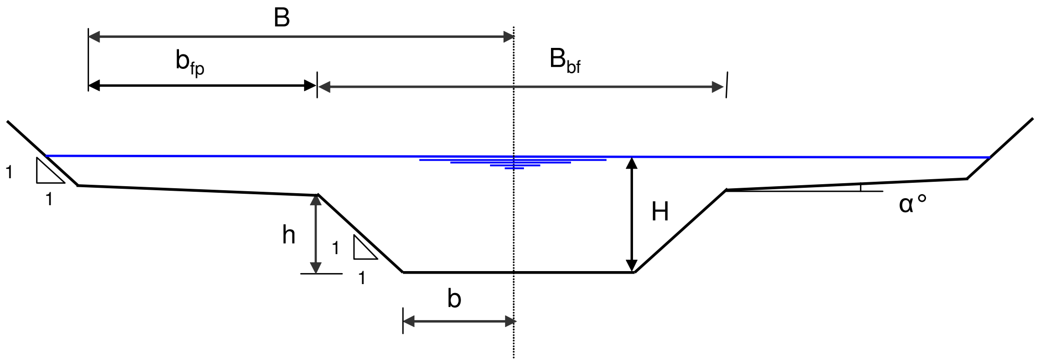

Figure 1 Notation in cross-section of generalised river model

Analysis of surveyed cross-sections within this reach indicated that the bankfull width of the main channel (B_{bf}) was approximately 25m. Furthermore, flood polygons made available by OPW suggested that the active floodplain on each side of the main channel extended for a width (b_{fp}) of approximately 25m. The main channel banks were inclined at 45^o to the horizontal and the estimated bankfull depth (h) was of the order of 2.5m. The floodplain boundaries were assumed to be also inclined at 45^o to the horizontal giving a trapezoidal overbank section in the generalised model. The main channel roughness was expressed in terms of Manning's n (n_{mc}) and assigned a value of 0.03 to account for channel irregularities, alignment, obstructions and vegetation. The longitudinal slope of the floodplain (S_{fp}) was set at 0.001 to coincide with the approximate observed value between Newbridge and Caher Park.

The generalised river model was executed for a range of input hydrographs for specified return periods. These were based on flow data from Newbridge gauging station (Station No. 16008) on the River Suir that is available from 1954 to 2006. The input hydrographs, shown in Figure 2 were derived from the methodology and its associated software that was developed in WP 3.1 of the FSU for gauged catchments.

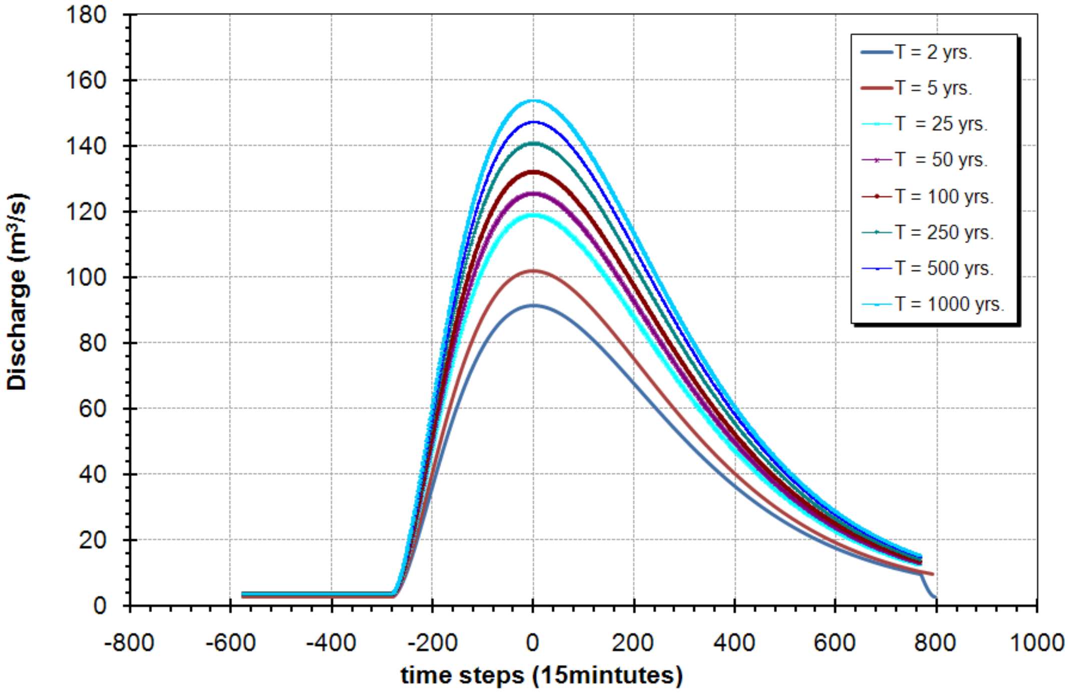

Figure 2 Input hydrographs in generalised river model

The simplifying assumption in the derivation of these hydrographs is that each hydrograph has the same base length. However, hydrograph duration is important in the context of floodplain attenuation and was incorporated into the analysis in this paper by developing triangular hydrographs (Figure 3) with flood durations between 1.75 hours to 2007.75 hours using FSR methodologies.

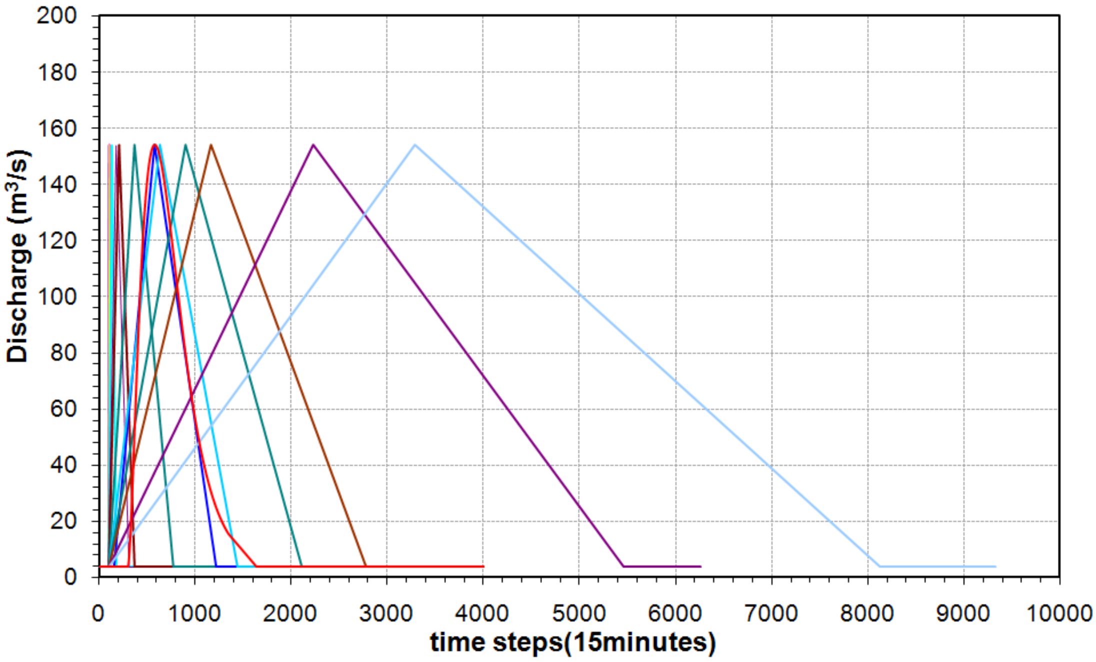

Figure 3 Input hydrographs of varying flood durations

In addition to hydrograph peak and duration, a range of geometrical properties that influence the storage and conveyance capacity of a channel were investigated. These are important factors in the attenuation of flood peaks and hydrograph deformation and include (i) floodplain length; (ii) floodplain longitudinal slope; (iii) floodplain resistance; (iv) floodplain width; (v) floodplain transverse slope; and (vi) main channel resistance. While literature highlights extensive energy losses, that result from the complexities of main channel and floodplain interactions in compound channels, the influences of these (sinuosity, width-depth ratio, channel side slope etc.) will be most pronounced in the low floodplain depth range and will diminish as the depth and flow increase. In the high flood flow range, the influence of the main channel in terms of the flow that it conveys and in terms of the energy losses from main channel floodplain interactions will be much less significant.

Simulations were undertaken for incremental changes of the important parameters as summarised in Table 1. Eight cases, denoted by A-H were examined. Case A investigated the channel length, Case B the longitudinal slope, Case C the floodplain roughness, Case D the floodplain width, Case E the floodplain transverse slope, Case F the flood peak flow, Case G the main channel roughness and Case H the flood duration.

Table 1 Summary of investigated model simulations

Case	L (km)	S_{fp} (m/km)	n_{fp} (s/m$^{1/3}$)	b_{fp} (m)	α (deg)	Q_P (m^3/s)	n_{mc} (s/m$^{1/3}$)	T_B (hrs)
Standard	50	1.00	0.25	25.0	0	153.90	0.03	335.5
A1 - A5	10 - 50	1.00	0.25	25.0	0	153.90	0.03	335.5
B1-B13	50	0.05 - 3.00	0.25	25.0	0	153.90	0.03	335.5
C1-C8	50	1.00	0.01 - 5.00	25.0	0	153.90	0.03	335.5
D1-D9	50	1.00	0.25	25 - 1500	0	153.90	0.03	335.5
E1-E6	50	1.00	0.25	25.0	0 - 30	153.90	0.03	335.5
F1-F8	50	1.00	0.25	25.0	0	91.41 - 153.90	0.03	335.5
G1-G10	50	1.00	0.25	25.0	0	153.90	0.03 - 5.00	335.5
H1-H13	50	1.00	0.25	25.0	0	153.90	0.03	1.75 - 2007.75

The influence of individual changes in these parameters was determined through comparison of the upstream input hydrograph with the simulated downstream hydrograph. Differences, expressed in terms of relative attenuation were determined and from these a multivariate regression model representing floodplain attenuation in terms of these parameters was developed. Interrogation of this model was undertaken to determine the required attenuation index.

RESULTS

The influence of each of the eight parameters on flood hydrograph attenuation was assessed by comparing the flood peaks of inflow hydrographs to the outflow hydrographs generated in model simulations as shown in Figure 4.

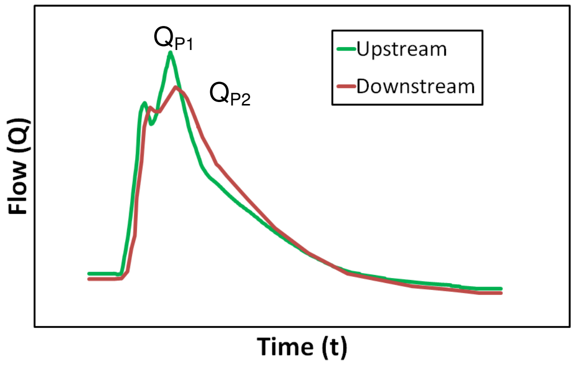

Figure 4 Schematic of inflow and attenuated outflow hydrographs

The difference in the peak flow of the upstream and downstream hydrographs is expressed in terms of % relative attenuation :

$$\% \text{ Relative attenuation} = \frac{Q_{P1} - Q_{P2}}{Q_{P1}} \times 100 \qquad \textbf{Eqn. 3}$$

where Q_{P1} and Q_{P2} are the peaks of the inflow and outflow hydrographs in Figure 4.

The influences of length, floodplain longitudinal slope, roughness, width, transverse slope, flood peak magnitude, main channel roughness and flood duration on relative flood peak attenuation are shown in Figure 5.

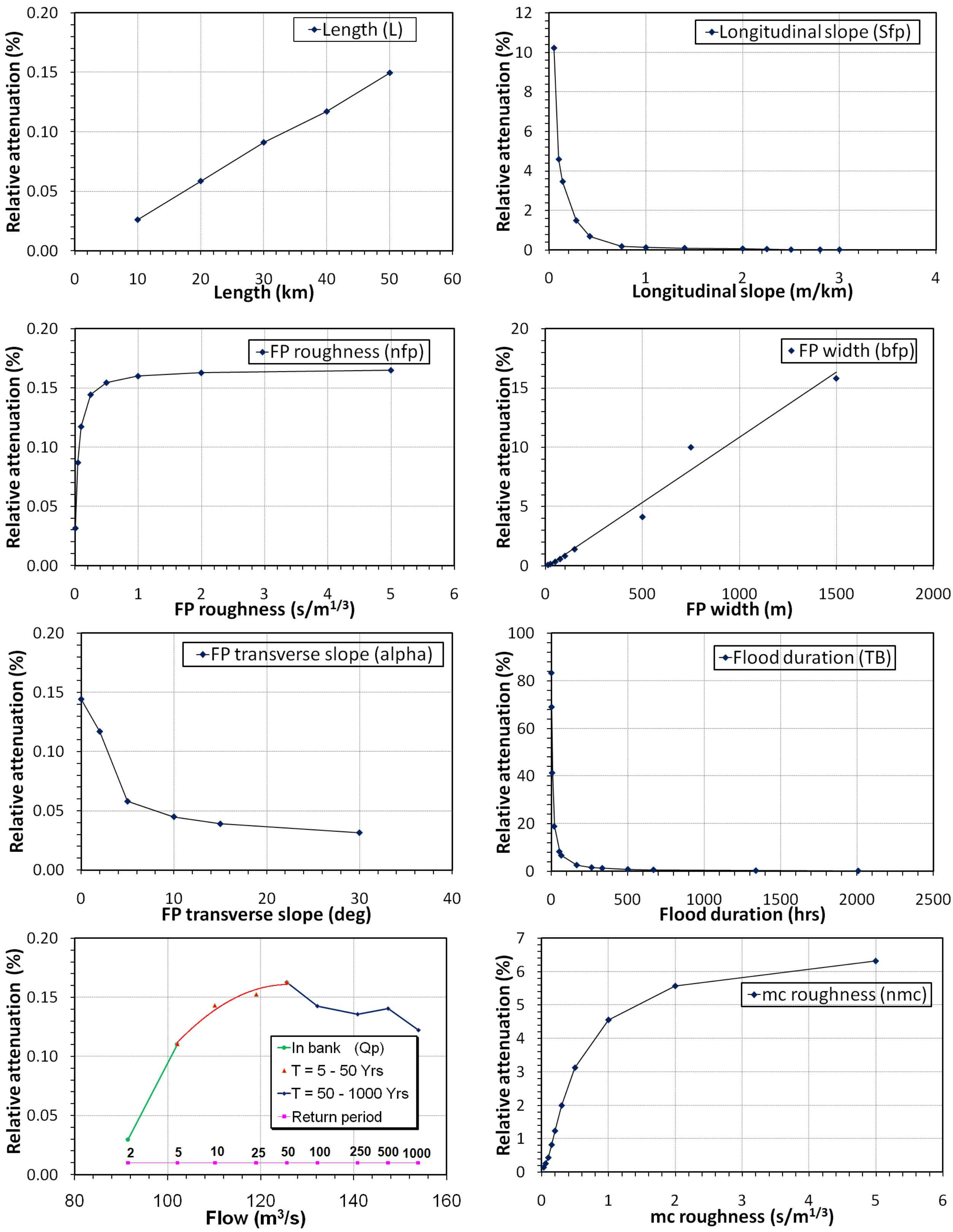

Figure 5 Influence of Floodplain, main channel and hydrograph properties on percentage of relative attenuation

Based on the results of these simulations, a simple index that allows for floodplain effects was developed from the multivariate regression model. This index is:

$$\% \textbf{ Relative attenuation} = 1.56\ \frac{L\ n_{fp}^{0.03} \left(\frac{b_{fp}}{B_{bf}}\right)^{1.10} n_{mc}^{0.83}\ Q_P^{1.04}}{S_{fp}^{1.54}\ T_B^{1.35}\ \alpha^{0.19}} \qquad \textbf{Eqn. 4}$$

where L is the floodplain length, n_{fp} is the floodplain Manning's resistance, b_{fp} is the average floodplain width on each side of the main channel , B_{bf} is the bankfull width of the main channel, n_{mc} is the main channel Manning's resistance, Q_P is the flood peak magnitude, S_{fp} is the floodplain longitudinal slope, T_B is the flood duration and α is the floodplain transverse slope. The performance of this index is shown in Figure 6 where the simulated relative attenuation values are compared to those calculated using Eqn. 4.

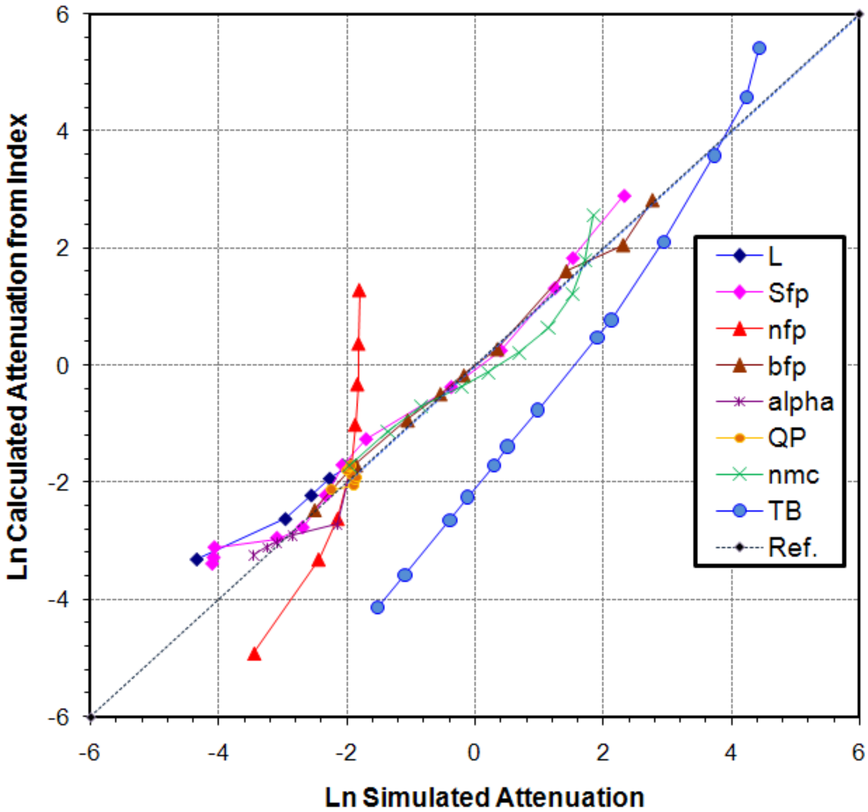

Figure 6 Comparison of simulated relative attenuations with those calculated using Eqn. 4

Eqn. 4 indicates that the exponent of the floodplain roughness is close to zero (0.03) and therefore suggests that the floodplain roughness is relatively insignificant for flood peak attenuation. Results in Figure 5 indicate that increases in floodplain Manning's roughness beyond a threshold value of approximately 0.4 result in limiting value relative attenuation for a given flood hydrograph. For these conditions, floodplain conveyance is diminished and the main channel of the compound section is the main conduit for conveying the flood flow. The inclusion of the high floodplain resistances (for Manning's *n* up to 5) that were investigated in the study and included in the best fit regression model would appear to be having an overly strong influence on the overall attenuation index in Eqn. 4. Figure 6 shows that lower volume floods characterised by short duration (T_B) can be attenuated to a much greater degree than larger volume events. Data in Figure 6 for flood duration (T_B) indicated that this parameter is contributing to underestimated attenuations when calculated using Eqn. 4. However, representing flood volume by two independent parameters, namely flood peak and flood duration, as is the case in the regression model does not reflect the situation in reality where a strong correlation is likely to exist between these parameters.

CONCLUSIONS

The parametric investigation conducted illustrates how channel and floodplain hydraulic and geometric properties can influence hydrographs of various frequencies and durations. Simulation results indicate that, the dominant influences on flood peak attenuation are flood duration, floodplain width and floodplain slope. It is also shown that the index represents attenuation more accurately for higher values than it does for those in the lower attenuation range. It should be noted at this point that Eqn. 4 is based solely on the assessed influence the investigated parameters on relative attenuation using the HEC-RAS model and has therefore limitations. The constant in the equation and the values of parameter exponents are based on the simulated data and further work is continuing to refine this equation based on the theoretical range of these values that may be expected to occur. The index is also being applied to field results in the River Suir catchment.

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REFERENCES

Choudhury, P. and Shrivastava, R.K. and Narulkar, S.M., 2002. Flood routing in river networks using equivalent Muskingum inflow. J. Hydrol. Eng. 7(6): 413-419.

Institution of Civil Engineers (1975). Flood studies conference. Discussion on papers 7 and 8, ICE, London, p. 61.

Mason, D.W 1992. Modelling the effect of floodplain storage on flood frequency curve. PhD thesis, University of Newcastle upon Tyne.

McCartney, M.P. and Naden, P.S., 1995. A Semi-Empirical investigation of the influence of flood-Plain Storage on Flood Flow. Journal of the Institution of Water and Environment Management 9(3): 236-246.

Natural Environment Research Council. Flood Studies Report. NERC, London. 1975.

Shaw, E.M., 1994. Hydrology in practice. TJ Press (Padstow) LTD, Cornwall UK.

Tewolde, M.H. and Smithers, J.C., 2006. Flood routing in ungauged catchments using Muskingum methods. Journal of Water South Africa 32(3): 379-388.
US Army Corps of Engineers., 2008. HEC-RAS, River Analysis System Hydraulic Reference Manual. Available from: http://www.hec.usace.army.mil/software/hec-ras/documents/HEC-RAS_4.0_Reference_Manual.pdf.