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Indexing Floodplain Effects for Flood Estimation

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Abstract: *Combining flood estimation methodologies with hydraulic models to provide a detailed and spatially coherent representation of flood risk can be problematic. One potential difficulty is that of double-accounting the attenuating effect of floodplain storage. This occurs when effects are represented in both the flood frequency estimation of the flow and also in hydraulic modelling and can be particularly important in the context of the increasing desire to combine hydrological and hydraulic models in a manner that provides a detailed and spatially coherent representation of flood risk. This paper presents an empirically derived index that represents floodplain effects on flood magnitude. A HEC-RAS 1-D hydraulic model was used to generate downstream flow hydrographs in a generalised river reach for defined upstream hydrographs encompassing a range of flows and durations. Geometrical and resistance properties in the reach were systematically varied. Relative attenuations were determined by analysing differences in upstream and simulated downstream hydrographs. The index was derived by relating flood peak attenuations to the channel characteristics in each simulation in a multivariate regression analysis.*

Keywords: *Flood estimation, floodplains, attenuation, river hydraulics, hydrology, flood frequency,*

1. INTRODUCTION

Understanding the interaction between the main channel and floodplains of two-stage channels remains a challenging topic in open channel hydraulics (Ghavasieh *et al*, 2005). The differences in river systems, together with their similarities under diverse settings, present complexities in defining the processes that influence the pattern and character of river systems (Rosgen, 1994). Floodplains act as weak forms of lakes or reservoirs and can provide an area of extra water storage during periods of overbank flow (Archer, 1989; Woltemade and Potter, 1994; McCartney and Naden, 1995). This effect in low gradient channels is likely to be more pronounced. In addition, the dispersal of water from the main channel to the floodplain alters flow velocities in overbank zones from momentum transfer mechanisms along the interface between main channel and floodplain zones (Sellin, 1964; Myers and Lyness, 1989; Ervine *et al*, 1994). At the point where bankfull levels are exceeded and floodplains become active for either conveyance and/ or storage, it is the physical characteristics of these overbank zones that are significant. These characteristics in terms of resistance and geometry have the capacity to both attenuate the flood peak and reduce the speed of flood wave propagation down the channel. Floodplain effects and the manner in which these are influenced by geometrical and resistance properties of the main channel and floodplain sections is therefore important in flood frequency analysis.

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 (AM) 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.

This study presents a simple 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. This produced downstream hydrographs for a variety of floodplain geometries and hydraulic resistances. Hydraulic flood routing procedures have been used to identify floodplain effects in previous studies. These methods of routing involve the numerical solutions of either the convective diffusion equation or the 1-D Saint–Venant equations for gradually varied unsteady flow in open channels (Tewolde and Smithers, 2006). HEC-RAS solves the 1-D Saint-Venant equations for gradually varied unsteady flow. Differences in flood peak between the observed upstream and simulated downstream hydrographs were expressed in terms of relative attenuation for a variety of geometrical and resistance parameters of a generalised two stage channel. These parameters are known to influence the attenuation capacity of river channels. The index was developed through multivariate regression modelling of these parameters.

2. METHODOLOGY

The approach that was 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 solves 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:

$$\frac{\partial A}{\partial t}+\frac{\partial \varphi Q}{\partial x_c}+\frac{\partial (1-\varphi)Q}{\partial x_f}=0 \qquad (1)$$

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

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

In these equations, Q is the total flow down the reach, A_c and A_f are the cross sectional areas 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 coefficient and S is the friction slope and subscripts c and f represent the main channel and floodplain respectively. The parameter ϕ specifies how flow is partitioned between the floodplain and channel and as shown, is dependent on K_c and K_f, the conveyances in the main channel and floodplain respectively.

The generalised reach analysed in this study is shown in Figure 1. This geometry is consistent with that of many medium sized Irish rivers and is based on a reach of the River Suir, Co. Tipperary where long records of detailed and good quality hydrometric data are available.

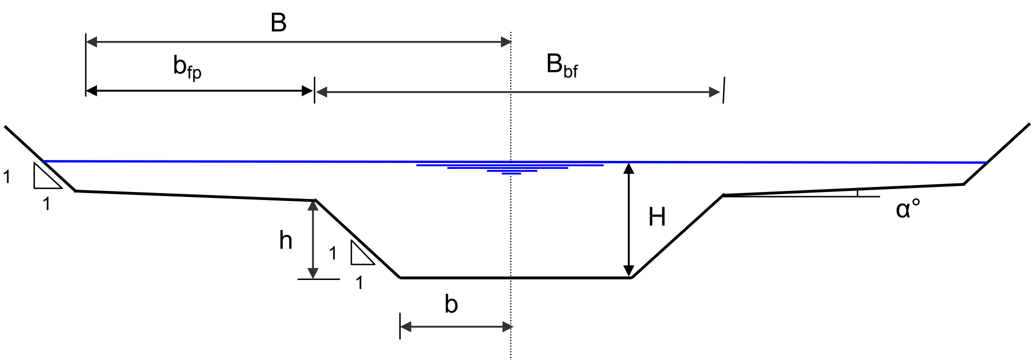

Figure 1 Notation in cross-section of generalised river model

Based on the River Suir, the generalised model was constructed with a bankfull width (B_{bf}) of 25m, and horizontal floodplains ($\alpha = 0^o$) that extended for 25 m (b_{fp}) on both sides of the main channel. Main channel side slopes were inclined at 45^o to the horizontal and the bankfull depth (h) was taken to be 2.5 m. The floodplain side slopes were also assumed to be inclined at 45^o to the horizontal, giving a trapezoidal overbank section in the 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 typical channel irregularities, alignment, obstructions and vegetation. The longitudinal slope of the floodplain (S_{fp}) was set at 0.001.

The generalised river model was executed for a range of input hydrographs for specified return periods (Figure 2). These were based on a 53-year flow record (1954 – 2006) of a gauging station on the river (Newbridge Station - No. 16008) and were developed from a methodology and its associated software that was developed as part of the Irish Flood Studies Update Programme (Reed and Martin, 2005) for gauged catchments.

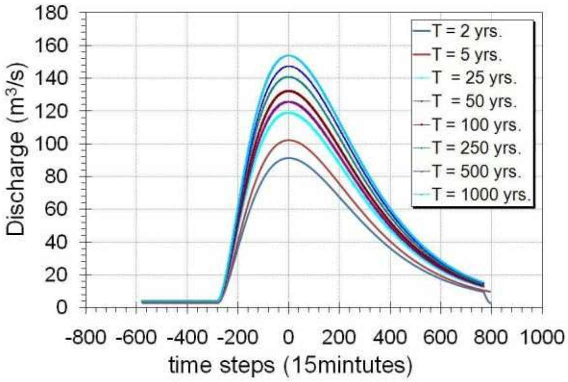

Figure 2 Input hydrographs in generalised river model

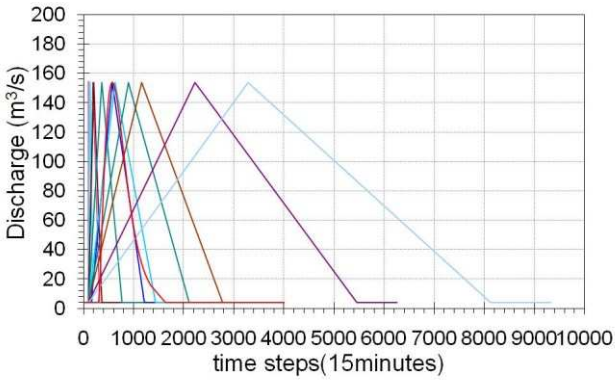

Figure 3 Input hydrographs of varying flood duration

The simplifying assumption in the derivation of the hydrographs in Figure 2 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 Flood Studies Report (FSR) (NERC, 1975) methodologies.

In addition to hydrograph peak (Q_P) and duration (T_B), 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 (L); (ii) floodplain longitudinal slope (S_{fp}); (iii) floodplain resistance (n_{fp}); (iv) floodplain width (b_{fp}); (v) floodplain transverse slope (α); and (vi) main channel resistance (n_{mc}). 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 and 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.

3. 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.

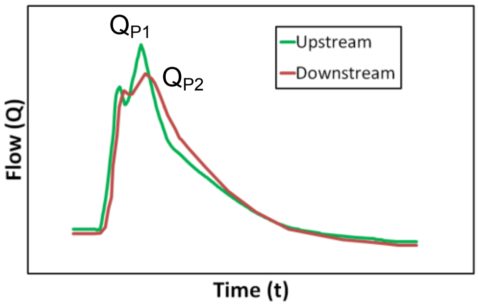

Figure 4 Schematic of inflow and attenuated outflow hydrographs

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

$$\%\ \text{Relative attenuation} = \frac{Q_{P1} - Q_{P2}}{Q_{P1}} \times 100 \qquad (3)$$

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

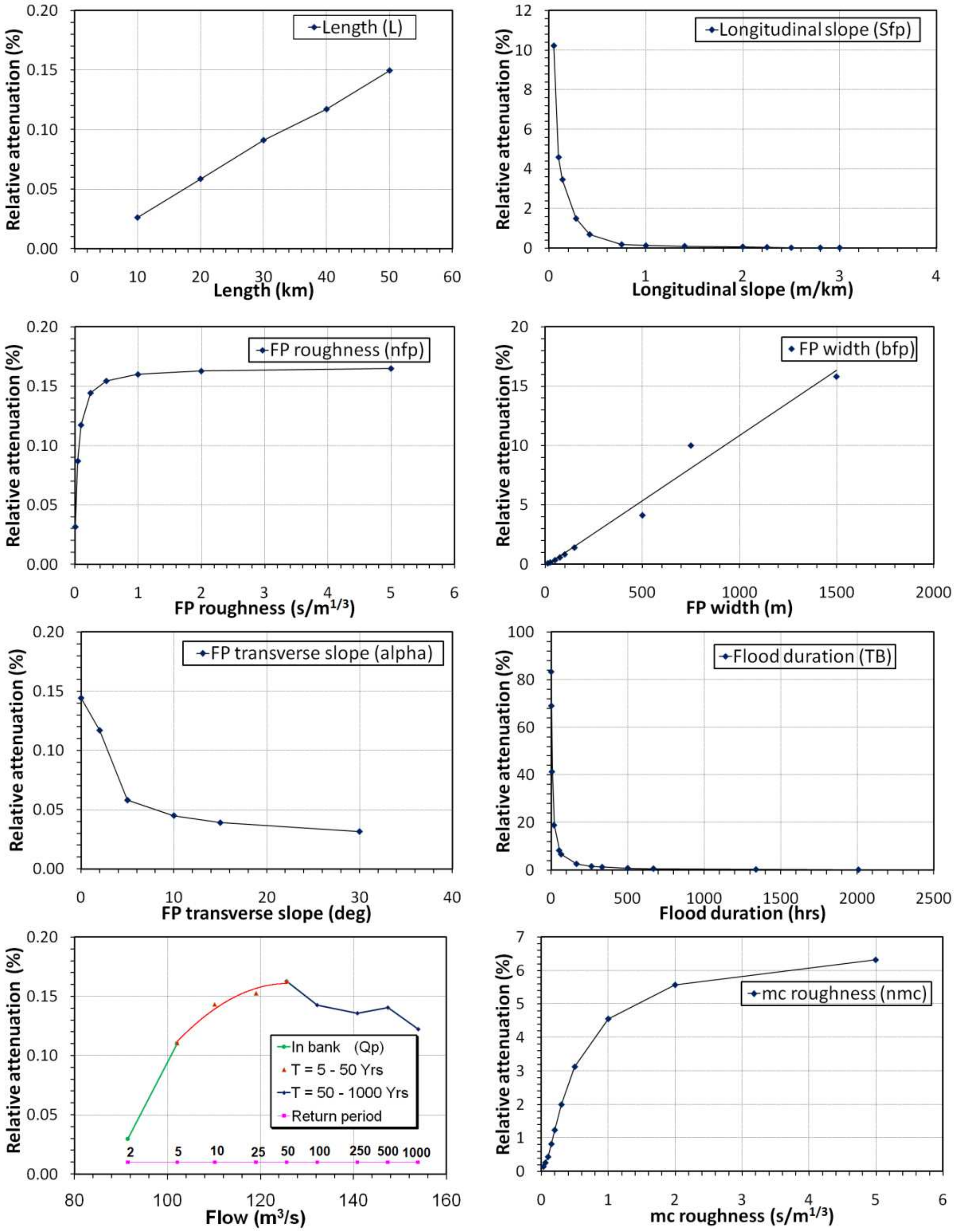

Figure 5 Influence of Floodplain, main channel and hydrograph properties on percentage of relative attenuation

Figure 5 indicates that relative attenuation increases linearly with reach length. This is consistent with other research where the influence floodplain properties on attenuation was investigated (e.g. Wolff and Burgess, 1994). Floodplain width, as would be expected, also has a strong influence on attenuation which increases with increasing width. The variation of relative attenuation with slope (S_{fp}) is included in Figure 5. The relative attenuations shown cover a range of gradients from 0.2 m/km to 3 m/km that are typical in Irish catchments. Results indicate that relative attenuation decreases to a limiting upper slope value of 1 m/km beyond which attenuation is negligible. At low gradients, significant attenuation of the flood peak is observed. Lower attenuation in steeper catchments reflects the higher conveyance associated with high gradient channels and the associated reduction in storage of the flood volume in the reach. The variation of relative attenuation with floodplain roughness (n_{fp}) is shown to increase before reaching a constant value as roughness continues to increase. This represents a limitation in the current analysis. Roughness in the hydraulic model is exerted along the wetted perimeter of the channel. In real rivers, floodplain roughness will have a different influence depending on the depth. For low flow depths, roughness may be expected to be emergent or surface penetrating. In this case, the resistance to the flow will primarily result from the drag influence of the elements and attenuation would be significant. As flow and water levels continue to increase, the same floodplain roughness would be expected to become submerged, resulting in an increase in floodplain conveyance and a corresponding reduction in attenuation. Attenuation is also shown to increase with increasing main channel roughness (n_{mc}) values but in this case a point is reached where the flow approaches stagnation and further changes in relative attenuation in this high roughness range are small. Results from the Case E analysis where floodplain transverse slope (a) was investigated indicates that increasing lateral gradients attenuate a progressively decreasing proportion of the flood peak. As a result compound channels with steep lateral slopes convey more water through the main channel than those with flatter slopes.

Furthermore, floodplain resistance is typically higher than that in the main channel and the low attenuations corresponding to the steeper lateral slopes are added to as the proportion of flow being retarded by this roughness is lower than would be the case in floodplains with lower transverse gradients. The variation of attenuation with increasing flow magnitude (also in Figure 5) is shown to be complex and is dependent on flow magnitude and floodplain depth. For return periods less than the bankfull return periods (typically between 1 and 2 years), floods will not significantly inundate the floodplain and will not be affected by the additional attenuation attributed to floodplain characteristics. Attenuation in these cases will result solely from the natural attenuation in the main channel alone and as shown, will be reasonably low. For moderate floods in the 5-year to 50-year return period range, the floodplain provides a significant area for extra storage of water and may result in decreased conveyance in the overbank channel zone. This is consistent with findings by Woltemade and Potter (1994) who observed that the attenuation of moderate volume floods, while being influenced by channel-floodplain morphology, valley width, stream slope, and hydraulic resistance, can be significant. As flows continue to increase to values for return periods greater than 50 years attenuation is shown to decrease and then approach a reasonably constant value. Floodplain resistance in the hydraulic model is defined in terms of Manning's *n* which represents a boundary resistance as opposed to drag resistance which would be significant for emergent vegetation. As flow and depth increase, this boundary resistance becomes relatively less significant in the context of the overbank flow volume being conveyed, resulting in an increase in overall velocity and a corresponding decrease in attenuation as shown. Flow duration is also shown to be important. As expected, Figure 5 indicates that hydrographs with sharp peaks but low volumes (short duration) experience significantly higher attenuation than those hydrographs with higher volumes. Floods that are characterised by high volumes on the rising limb of the hydrograph will tend to occupy floodplain storage that is available and once occupied, this storage is no longer available for the remainder of the flood. The attenuation provided by the floodplain in these high volume floods is therefore less significant. In contrast, hydrographs with low rising limb volumes disperse most of the flood volume to storage resulting in relative attenuations that are high.

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

$$\%\ \text{Relative attenuation} = 33\,\frac{L\, n_{fp} \left(\dfrac{b_{fp}}{B_{bf}}\right) n_{mc}\, Q_P^{\,1.22}}{S_{fp}^{1.53}\, T_B^{1.92}\, \alpha^{0.20}} \qquad (4)$$

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.

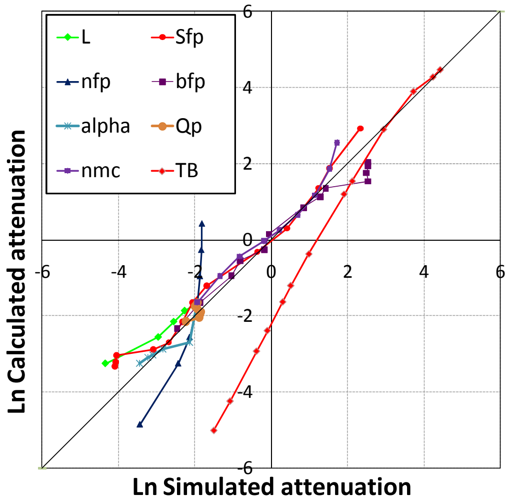

Figure 6 Comparison of simulated relative attenuations with those calculated using Eqn. 4

Figure 6 indicates that Eqn. 4 reproduces reasonably well the simulated data for most of the geometrical, resistance and hydrograph properties. The data indicates that the main sources of error in Eqn. 4 arise from the representation of flood duration (T_B) and floodplain resistance (n_{fp}). Results in Figure 5 indicate that increases in floodplain Manning's roughness beyond a threshold value of approximately 0.4 result limit the 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. A reason for the poor fit of flood duration to simulated values may relate to the assumption of independence between the flood peak (Q_P) and the flood duration (Figure 3) that was made in including duration as a parameter in the regression model.

Figure 6 also indicates that Eqn. 4 is more accurate at predicting high flood peak attenuations. Therefore the poor fit that is evident in the bottom left corner of Figure 6 is likely to be less of a concern to the flood estimator who will typically be unconcerned with low values of attenuation.

4. CONCLUSIONS

The investigation presented 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. A simple index based on a multivariate regression analysis of the influential channel and hydrograph properties is also presented. It is 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 of the investigated parameters on relative attenuation using the HEC-RAS model and therefore, has limitations. The constant in the equation and the values of parameter exponents are based on the simulated data and further work is required to refine this equation based on the theoretical range of these values that may be expected to occur. The index also requires validation for natural channels where complexities will be significantly increased. This work is ongoing and the index will initially be applied to the River Suir catchment in Co. Tipperary, Ireland.

5. REFERENCES

Archer, D. (1989), *Flood wave attenuation due to channel and floodplain storage and effects on flood frequency.,* in Beven, K. and Carling, P.A., "Floods: Hydrological, Sedimentological and Geomorphological Implications", John Wiley and Sons, Chichester, pp. 37-46.

Conor, T.B., Ahern, P.A. Woodhouse, M.P. and Ford, B.R. (1984), *Application of Mathematical Flood Plain Modelling, The Engineering Conference*, Brisbane, April 2 – April 6, 1984, pp. 304-308.

Ervine, D.A., Sellin, R.J. and Willetts, B.B. (1994), *Large flow structures in meandering compound* channels, in White, W.R., and Watts, J. (Eds) *2nd International conference on River Flood Hydraulics* York, England, March, 1994, Published by John Wiley and Sons Ltd, Paper 40, pp. 459-469.

Ghavasieh A.R., Poulard C. and Paquier A. (2006). *Effect of roughened strips on flood propagation: Assessment on representative virtual cases and validation*, J. Hydrol., 318: 121-137.

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.

Myers, W.R.C. and Lyness, J.F. (1989), *Flow resistance in rivers with floodplains*, Final Report on Research Grant GR5/D/45437, University of Ulster, Northern Ireland.

NERC (Natural Environment Research Council), (1975), *Flood Studies Report. Vol. I Hydrological Studies. Vol II Meteorological Studies. Vol III Flood Routing Studies. Vol IV Hydrological Data. Vol V Maps,* London.

Reed, D and Martin, J. (2005) FSU: A new look at flood estimation for Ireland. Proc. of UNESCO International Hydrological Programme, OPW (Ireland) National Hydrology Seminar, 26 – 33.

Rosgen, D.L. (1994). A classification of natural rivers. Catena., 22, 169-199.

Sellin, R.H.J. (1964), *A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain.* La Houille Blanche, November, 19(7), 793-801.

Tewolde M.H. and Smithers J.C. (2006), *Flood routing in ungauged catchments using Muskingum method*s, Journal of Water South Africa, 32(3), 379-388.

Wolff, C. G. and Burges, S. J., (1994), *An analysis of the influence of river channel properties on flood frequency*, J. Hydrol., 153, 317-337.

Woltemade C.J. and Potter, K.W. (1994). *A watershed modelling analysis of fluvial geomorphologic influences on flood peak attenuation,* Water Resour. Res., 30(6), 1933-1942.