Office of Public Works

Flood Studies Update Programme
Work package 3.5
IBIDEM (Interactive Bridge Invoking the Design Event Method)

Final Report

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CONTRACT

This report describes work commissioned by the Office of Public Works under their letter of 24 December 2008. The OPW's representative for the contract was Dr John Martin. Duncan Faulkner, Zoë Whiteman, Kevin Haseldine, Ann-Marie Gray and Mark Morris of JBA Group and Duncan Reed of DWRconsult carried out the work.

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PURPOSE

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EXECUTIVE SUMMARY

IBIDEM stands for Interactive Bridge Invoking the Design Event Method. The idea of the project is to provide a bridge between the FSU method of estimating a design flood hydrograph and the FSR design event method that it replaces. Two parameters of the FSR rainfall-runoff model (time to peak and standard percentage runoff) are chosen by optimisation so that the design hydrograph synthesised by the FSR method matches that produced by the FSU procedures.

This final report describes the IBIDEM software package which is a web-based application that has been developed by JBA Consulting to meet the technical specification produced by the Office of Public Works.

The report explains the calculations that IBIDEM carries out, describes how the results are presented and presents an account of how IBIDEM has been tested for five example catchments. The tests have shown that IBIDEM can provide a useful way of assessing design flood hydrographs produced from the FSU procedures and can help in spotting cases where the shape of the hydrograph or the peak flow appear to be unrealistic given the properties of the catchment.

A brief user guide to the software is included in Appendix A.

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CONTENTS

LIST OF FIGURES

ABBREVIATIONS

ANSF	Average non-separated flow (baseflow) (m^3/s)
AREA	Area (km^2)
ARF	Areal Reduction Factor
BF	Baseflow (m^3/s)
CWI	Catchment Wetness Index
DDF	Depth Duration Frequency
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
FSSR	Flood Studies Supplementary Report
IBIDEM	Interactive Bridge Invoking the Design Event Method
OPW	Office of Public Works
P	Precipitation depth (mm)
PR	Percentage Runoff
RMED	Median annual maximum rainfall depth (mm)
RMSE	Root Mean Square Error
SAAR	Standard Average Annual Rainfall (mm)
SPR	Standard percentage runoff
Tp	Time to Peak (hours)
URBEXT	Index of urban extent (in IBIDEM this is treated as a proportion, varying from 0 to 1)
W50	Hydrograph width at 50% of the flow (hours)
WP	Work Package (within the Flood Studies Update research programme)

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1 INTRODUCTION

1.1 Purpose of this report

IBIDEM stands for Interactive Bridge Invoking the Design Event Method. The idea of the project is to provide a bridge between the Flood Studies Update method of estimating a design flood hydrograph and the FSR design event method that it replaces.

This final report has been issued along with the IBIDEM software. The report explains how the software works, what methods it uses to fit hydrographs, the various options it offers and what inputs and outputs are needed. It also describes how the software has been tested.

Appendix A is a brief stand-alone user guide which takes the user through the steps needed to operate the software.

1.2 Brief

The specification for the project is set out in the tender documents from the Office of Public Works (OPW), dated September 2008. The purpose of the project is to develop a software tool linking Flood Studies Update (FSU) design hydrographs to the Flood Studies Report (FSR) design event (rainfall-runoff) method.

2 BACKGROUND TO PROJECT

2.1 Hydrograph estimation by FSU methods

In the Flood Studies Update approach, the T-year peak flow is estimated as the product of an index flood estimated by methods developed in work package (WP) 2.3 and a growth curve estimated by WP2.2 methods. The design hydrograph is then constructed around the peak flow by applying a hydrograph shape (estimated by WP3.1 methods).

WP3.1 offers two options for specifying a hydrograph shape:

- An empirical approach, for sites where flow data is available, in which the hydrograph shape is built up using widths extracted from observed hydrographs for given percentages of the peak flow. This analysis can be carried out using the HWA software developed during WP3.1.
- A synthetic approach for ungauged sites, with two variants: firstly a parametric function (gamma curve plus exponential recession) with parameters estimated from catchment descriptors, and secondly a non-parametric method which involves specifying the width of the hydrograph at the 75 and 50 percentiles of the peak flow and an eccentricity to indicate the skewness of the hydrograph. Where the full hydrograph is needed, the parametric "curve descriptors" function is recommended, with the non-parametric "width descriptors" method suggested for applications where only the upper part of the hydrograph is needed.

2.2 Hydrograph estimation by the FSR design event method

The T-year design hydrograph is constructed as the output to the "unit hydrograph/losses" rainfall-runoff model. The FSR design event method combines four inputs: the temporal profile, duration, and rarity of the rainfall event and the pre-event catchment wetness. The first three define the rainfall input (to the rainfall-runoff model), whilst the fourth defines the initial condition (of the rainfall-runoff model). These inputs take specific values according to particular rules (see Figure 2-1). The rules reflect some of the general properties of the catchment and its climate.

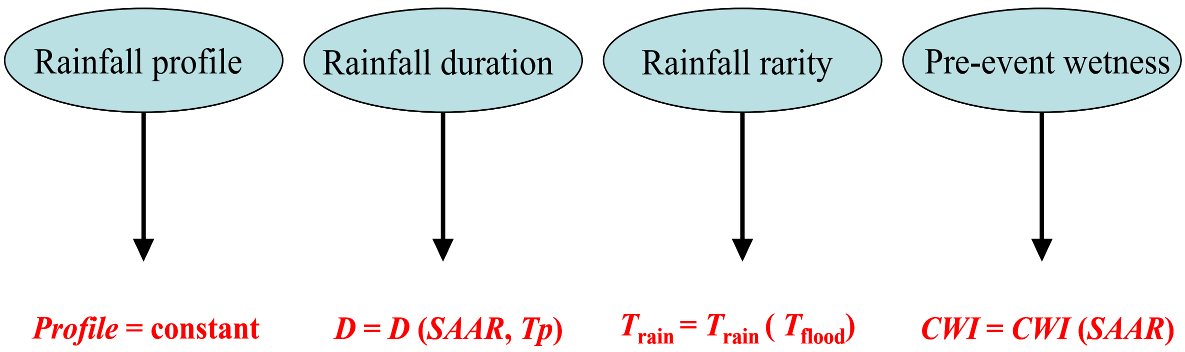


Figure 2-1: Design inputs to FSR rainfall-runoff method of flood frequency estimation

It is necessary to adopt suitable values for the parameters of the rainfall-runoff model itself. For the FSR "unit hydrograph/losses" model, these are the standard percentage runoff (SPR), the unit hydrograph time-to-peak (Tp) and the standardised baseflow, known as "average non-separated flow" (ANSF). On all but highly permeable catchments, the last parameter tends to be relatively unimportant. Two other factors play a central role in the model: the catchment area (AREA), and the areal reduction factor (ARF) applied to estimate the design catchment rainfall (from the design rainfall depth for a typical point within the catchment).

In the FSU, the rainfall depth-duration-frequency model derives from the statistical analysis of rainfall undertaken for Met Éireann by Fitzgerald and Walsh.

2.3 Basic idea of bridge between the FSR and FSU methods

The basic idea of the project is to provide a bridge between the FSU method of T-year hydrograph estimation and the FSR rainfall-runoff method it replaces. The Tp and SPR parameters of the rainfall-runoff model are chosen so that the design hydrograph synthesised by the FSR method matches that produced by the FSU procedures. The approach offers several gains:

- The whole hydrograph is synthesised, not just the upper part (as in the empirical and non-parametric methods developed in WP3.1). This will allow the user to look at runoff volumes (e.g. for assessing flood storage), and to route hydrographs, as they do with the FSR rainfall-runoff method.
- A link with rainfall is made. By noting the percentage runoff (PR) and the rainfall duration (D) implied by the bridge, the user will be able to check that the FSU design hydrograph is consistent with what is expected of the particular catchment.
- Those with particular experience of the FSR design event method will be able to interpret the Tp and SPR parameters of the rainfall-runoff model to which the FSU design hydrograph is said to be equivalent, comparing these to the values expected for such catchments. They may also wish to vary these values to investigate their effect on the flood hydrograph.

3 HOW IBIDEM FITS HYDROGRAPHS

3.1 Overview

IBIDEM works by importing a hydrograph which will have been derived using FSU methods and fitting a FSR rainfall-runoff hydrograph to match the shape and peak flow of the FSU hydrograph. The fitting is carried out by adjusting the FSR rainfall-runoff parameters time to peak (Tp) and standard percentage runoff (SPR).

Section 3.2 describes how IBIDEM implements the rainfall-runoff method. Numerous runs of the method are performed during the hydrograph fitting process in IBIDEM. Section 3.3 describes the approach that IBIDEM follows for fitting hydrographs. The details of the calculation of Tp and SPR are given in Sections 3.4 and 3.5.

3.2 Implementation of the FSR rainfall-runoff method

IBIDEM implements all parts of the FSSR16 version of the rainfall-runoff method apart from the calculation of time to peak and standard percentage runoff from catchment characteristics, because these parameters are derived by optimisation in order to fit the imported FSU hydrograph.

For running the rainfall-runoff method, the software carries out the following steps:

1. Imports the catchment descriptors AREA, SAAR and URBEXT (the latter is needed to adjust the percentage runoff).

2. Takes values of SPR and Tp supplied by the optimisation routine (or the adjustments provided by the user for some options).

3. Selects an appropriate data interval ΔT based on Tp, adopting a suitable convenient value such as 0.25 hours or 1 hour.

4. Calculates the design rainfall duration D from Tp and SAAR and the areal reduction factor (ARF) from AREA and D using the formula developed by Keers and Wescott (1977)[1], which is used in the Micro-FSR software.

5. Creates a triangular unit hydrograph using the Tp value.

6. Calculates the design rainfall depth from D and a user-supplied flood return period[2] (or set of return periods). The user-supplied flood return period is converted to a rainfall return period using the appropriate FSR design package.

   IBIDEM requires the rainfall depth for a typical (i.e. average) point in the catchment. Within IBIDEM, this is multiplied by the ARF to give the catchment-average rainfall for the required return period. The user needs to enter a table of average point rainfall depths for a set of durations and return periods. This information will have been calculated outside IBIDEM by averaging across the individual results for 2km grid points that fall within the catchment. The table is in CSV format, with durations (0.25 - 600 hours) in rows and return periods (2 - 200 years) in columns. IBIDEM calculates the required rainfall depth by interpolation, using linear interpolation between different durations and logarithmic interpolation between different return periods.

[1] Keers and Wescott, 1977. A computer-based model for design rainfall in the UK. *Met. Office Scientific Paper No. 36.* HMSO, London.

[2] Note: in line with the terminology used in the specification, IBIDEM quotes flood rarity using return periods rather than annual exceedance probabilities.

7. Distributes the rainfall depth according to the temporal profiles defined by the FSR (75% winter or 50% summer). As required in the specification, winter is the default setting (even on an urbanised catchment), and the alternative of summer can be chosen by the user.

8. Calculates the percentage runoff, PR, from SPR, rainfall depth and catchment wetness index, CWI, applying an urban adjustment if necessary. The urban adjustment is calculated as per Appendix A of the specification, so that it is based on URBEXT from the FSU rather than URBAN from the FSR, i.e.:

   $$PR = PRrural\ (1.0 - 0.47\ URBEXT) + 70\ (0.47\ URBEXT)$$

9. Applies the PR to the total rainfall profile to create a net rainfall profile.

10. Convolves the unit hydrograph with the net rainfall profile to give the rapid response hydrograph.

11. When necessary, adds baseflow to give the total runoff hydrograph. Baseflow is calculated from AREA, SAAR and CWI using the standard equation from Flood Studies Supplementary Report 16.

3.3 General approach taken for optimisation

3.3.1 First Tp and then SPR

The two parameters that the specification states are to be fitted, Tp and SPR, affect the hydrograph in different ways. SPR affects only the magnitude of the flows. In typical catchments where baseflow is relatively low, the magnitude of the flows is almost proportional to SPR (see the example in Figure 3-1 below).

Tp affects both the timing and the magnitude of the flows. A shorter Tp value alters the flow magnitude in three ways: firstly, it forces an increase in the peak of the unit hydrograph (to maintain the same volume of flow in a shorter time); secondly, it decreases the design storm duration, hence increasing the rainfall intensity for a given return period; and thirdly, the change in rainfall depth can affect the percentage runoff via the DPR_{RAIN} term (which is defined in Section 3.5). The effect of Tp on the peak of the modelled hydrograph for an example 11km^2 catchment is illustrated in Figure 3-1.

Because SPR has no effect on the timing, it is possible to optimise Tp first and then adjust SPR to give the desired flow magnitude.

An alternative approach would be to include the SPR parameter in the optimisation, allowing it to vary in order to achieve as good a fit as possible over the whole duration of the hydrograph. It would be necessary to compare the actual hydrographs in m^3/s rather than the dimensionless hydrographs because fitting the latter would not provide a value for SPR.

The approach chosen in IBIDEM is to calculate SPR after Tp, so that the resulting FSR hydrograph has a peak flow that matched that given by the FSU hydrograph. A possible disadvantage of this approach is that the overall shape match could be worse because of the lack of flexibility in the fitting. However, it has several advantages:

- The resulting FSR hydrograph is likely to be more useful (e.g. in river modelling) in that it exactly matches the best estimate of peak flow from FSU methods.
- It avoids some difficulties associated with defining the objective function when the optimisation is carried out comparing widths of actual hydrographs in m^3/s. If the FSR and FSU hydrographs have different peak flows (and the FSR peak changes after each iteration) then it is not clear what range of flows should be used for defining the objective function.

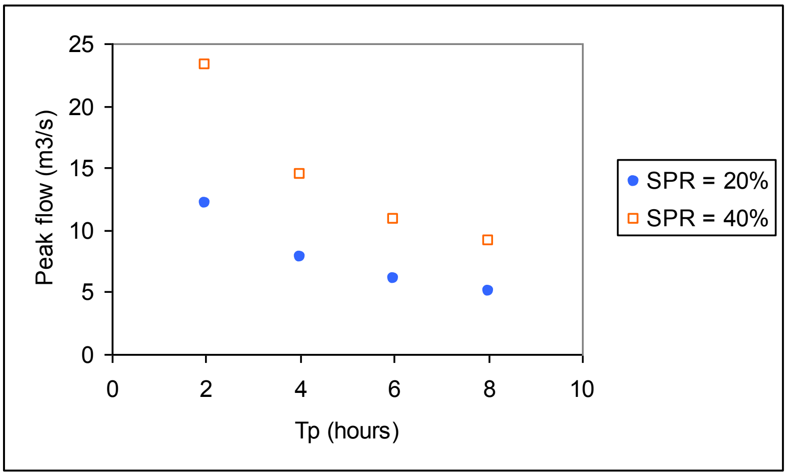


Figure 3-1: Variation of peak flow with Tp and SPR

3.3.2 Horizontal fitting

The specification suggests that horizontal fitting (i.e. in terms of time units) might be preferable to vertical fitting (i.e. in terms of flow units). This is the approach that has been taken for IBIDEM (Figure 3-2). It is consistent with the empirical method applied in WP3.1 to construct design hydrograph shapes, where the hydrograph shape is built up using widths at given percentages of the peak flow. Fitting is carried out for the portion of the hydrograph that lies above a threshold flow, largely because typical design hydrographs do not cover the full range of flows down to zero.

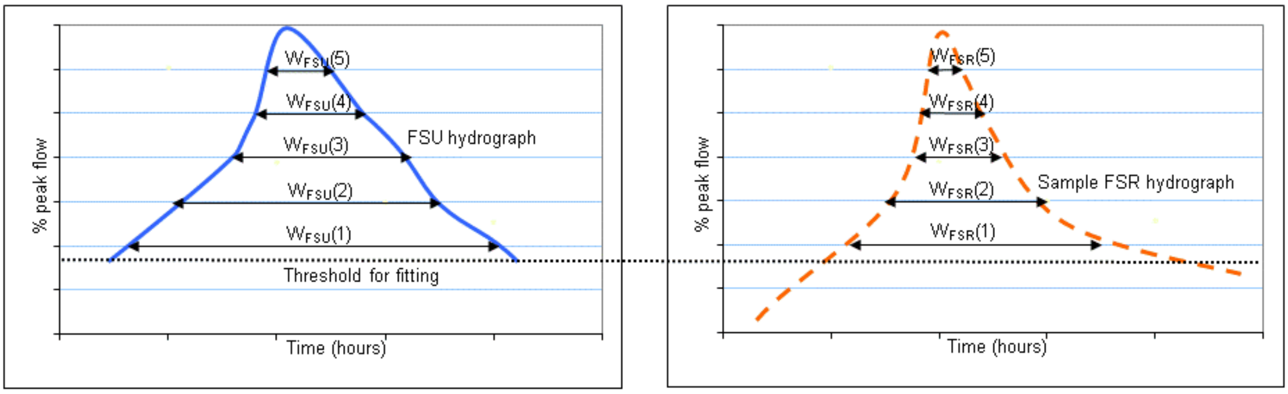


Figure 3-2: Horizontal fitting by comparing hydrograph widths

3.3.3 Deriving Tp by fitting the shape of the rapid response hydrograph

Tp is obtained by optimising the shape of the FSR rainfall-runoff hydrograph so that it matches the shape of the FSU hydrograph. These semi-dimensionless hydrographs are expressed as a percentage of peak flow.

One slight complication is that baseflow is defined as a fixed amount in m^3/s rather than a proportion of the peak flow. This has been overcome by fitting the shapes of the rapid response parts of the hydrographs, i.e. subtracting the (fixed) FSR baseflow from the FSU hydrograph (Figure 3-3).

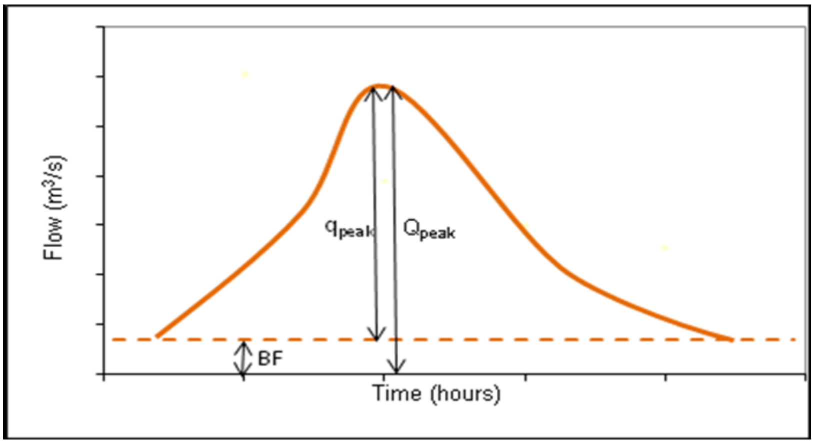


Figure 3-3: Relationship between peak flow Q_{peak} and peak rapid response q_{peak}

The steps in the calculation are:

1. Calculate the baseflow, BF, from the FSSR 16 equation.
2. Subtract BF from the FSU hydrograph. The peak flow Q_{peak} will be reduced to the response peak q_{peak}.
3. Express the threshold for fitting as a % of q_{peak}, i.e. $\%q_{threshold} = \%Q_{threshold} - 100(BF/Q)$

   (as the user will supply the threshold as a percentage of the total peak flow, $\%Q_{threshold}$)

   The user is prompted if they enter a threshold that equates to less than or equal to baseflow, BF, calculated in Step 1.
4. Calculate a set of *m* widths W_{FSU} of the FSU response hydrograph for percentage flows between $\%q_{threshold}$ and 100%, at an interval of 1% (see Figure 3-2).
5. Run the FSR rainfall-runoff method with an arbitrary (fixed) SPR and an initial guess for Tp.
6. Calculate a set of widths W_{FSR} of the FSR response hydrograph at the same percentages as in Step 4 (see Figure 3-2).
7. Calculate the objective function $\Sigma[W_{FSU}(i) - W_{FSR}(i)]^2$ for $i = 1$ to m.
8. Iterate, repeating steps 5 to 7 and varying Tp until the objective function is minimised (see section 3.4 below).

The empirical approach from WP3.1 may sometimes produce hydrographs with more than one peak (Figure 3-4). These cases are treated by excluding the time when flow is below the relevant percentage of the peak when evaluating the width of the hydrograph. This means that IBIDEM will give a realistic match to the total duration of the hydrograph (rather than just fitting one peak), but without being unduly affected by the separation of the peaks. The output from IBIDEM will always be a single-peaked hydrograph.

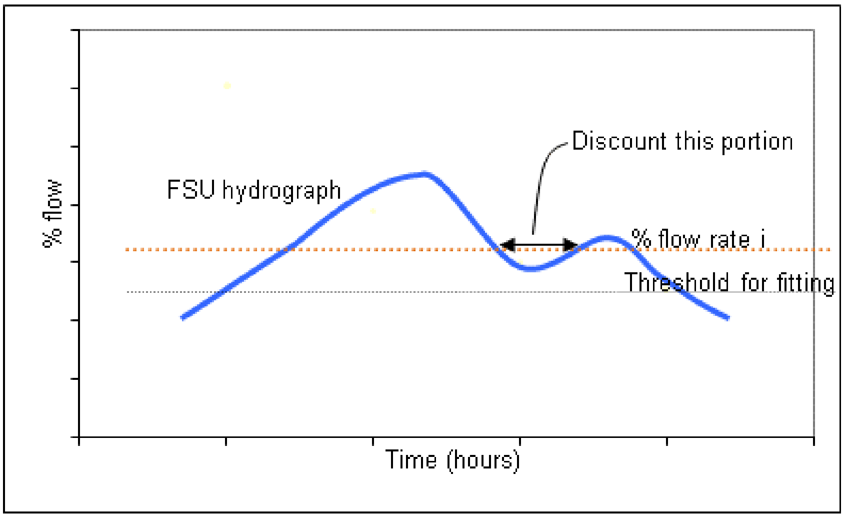


Figure 3-4: Double-peaked hydrograph

3.3.4 Deriving SPR by matching the required peak flow

After Tp has been optimised, the FSR hydrograph is scaled to fit the required peak flow which will have been derived from FSU methods. SPR is calculated by working out the factor by which the hydrograph has to be multiplied to match the FSU peak flow. Section 3.5 describes the calculations required.

3.4 Method for calculation of Tp

Calculation of Tp involves minimising the objective function given above. The minimisation is straightforward because it only involves one variable. We have therefore used a simple approach, which is based on bisection.

The starting point for the search is an initial guess for Tp, which is set to the time between the first ordinate and the peak of the input FSU hydrograph (it is not necessary to start with a particularly good guess). The search range is set as follows:

Minimum = 0.001 hours

Maximum = 10 times initial guess

This range of extreme values is likely to far exceed the realistic range in which the best parameter value lies, but there is little penalty in terms of run time for adopting such a wide range as a precautionary measure.

IBIDEM calculates five trial values of Tp in each iteration. For the first iteration, the values are:

Tp[1] = 0.001	i.e. the minimum which will be considered
Tp[2] = (Tp[1] + Tp[3]) /2	i.e. half way between Tp[1] and Tp[3]
Tp[3] = initial guess	
Tp[4] = (Tp[3] + Tp[5]) /2	i.e. half way between Tp[3] and Tp[5]
Tp[5] = 10 x initial guess	i.e. the maximum which will be considered

Each of the five trial values of Tp is used to create an FSR hydrograph shape. The value, Tp[n], that gives the best fit (i.e. the smallest value of the objective function) is used as the central value for Tp in the next iteration. Trial values for Tp are reassigned as follows:

Tp[1] = Tp[n-1]	i.e. updates lower bound to range in which optimum lies
Tp[2] = (Tp[1] + Tp[3]) /2	i.e. half way between Tp[1] and Tp[3]
Tp[3] = Tp[n]	i.e. best value from previous iteration
Tp[4] = (Tp[3] + Tp[5]) /2	i.e. half way between Tp[3] and Tp[5]

Tp[5] = Tp[n+1]   i.e. updates upper bound to range in which optimum lies

Iteration continues until Tp[5] - Tp[1] < 0.01. At that point, the value giving the best fit is used as the final value of Tp.

As an example, if the starting value of Tp is 5 hours and the ultimate best fit is given by the Tp value that is closest to 3 hours, the values used in the first few iterations would be as shown below, where the best fitting value for each iteration is shown in bold.

Table 3-1: Example illustrating iteration for Tp

Iteration	First	Second	Third	Fourth	Fifth
Tp[1]	0.001	0.001	1.25	2.5	2.81
Tp[2]	**2.5**	1.25	1.87	2.81	**2.96**
Tp[3]	5	**2.5**	2.5	**3.12**	3.12
Tp[4]	27.5	3.75	**3.12**	3.43	3.27
Tp[5]	50	5	3.75	3.75	3.43

After five iterations the Tp value is already very close to the best value of 3 hours.

3.5 Method for calculation of SPR

Having determined Tp by fitting the semi-dimensionless hydrographs, IBIDEM calculates SPR by matching the peak of the FSR response hydrograph, q_{peak}, to the required response peak from the FSU hydrograph, q^{FSU}_{peak}, which is found by subtracting BF from the peak FSU flow.

The calculation of SPR follows from the fact that the response hydrograph is directly proportional to the percentage runoff, PR. In the general case of a part-urbanised catchment,

$$PR = PR\mathrm{rural}\ (1.0 - 0.47\ URBEXT) + 70\ (0.47\ URBEXT) \qquad (3.1)$$

(this equation is from Appendix B of the specification, which expresses the FSSR16 urban adjustment for PR in terms of the FSU catchment descriptor URBEXT rather than the original FSR catchment characteristic URBAN).

Simplifying Equation 3.1 gives

$$PR = PRrural\ (1 - 0.47\ URBEXT) + 32.9\ URBEXT \qquad (3.2)$$

And PRrural is composed of three parts:

$$PRrural = SPR + DPR_{CWI} + DPR_{RAIN} \qquad (3.3)$$

Where SPR is standard percentage runoff, DPR_{CWI} is dynamic percentage runoff attributable to catchment wetness and DPR_{RAIN} is dynamic percentage runoff attributable to event rainfall.

The latter two quantities depend solely on catchment descriptors (SAAR, which controls CWI) and the design rainfall depth, which is a function of storm duration, which can be determined from Tp.

Without carrying out any convolution, it is possible to calculate q_{peak} as a function of PR using the “short-cut” method described in Flood Studies Supplementary Report 9:

$$qpeak = RC.(PR/100).(P/D).AREA \qquad (3.4)$$

where: RC is a routing coefficient which depends on D/Tp (a function of SAAR)

P is the depth of the design storm (after application of ARF)

D is the duration of the design storm

FSSR9 includes a graph showing how RC varies with D/Tp based on the 75% winter rainfall profile. A similar graph is presented in Volume 4 of the FEH, which includes a line corresponding to the 50% summer rainfall profile.

From Equations 3.2 to 3.4 IBIDEM calculates the value of SPR that gives the required q_{peak}. It is found from:

$$SPR = PRrural - DPR_{CWI} - DPR_{RAIN}$$

$$= \frac{PR - 32.9\ URBEXT}{1 - 0.47\ URBEXT} - DPR_{CWI} - DPR_{RAIN}$$

$$= \frac{\frac{100.D.q_{peak}}{RC.AREA.P} - 32.9\ URBEXT}{1 - 0.47\ URBEXT} - DPR_{CWI} - DPR_{RAIN} \qquad (3.5)$$

IBIDEM evaluates RC from a digitised version of the graph in FEH Volume 4 Figure 3.10 (with the y axis quantities divided by 10 to correct a mistake in the FEH). The fact that RC is found graphically introduces a slight uncertainty to the calculation of SPR, but this has been found to be small.

4 ADDITIONAL OPTIONS PROVIDED BY IBIDEM

4.1 Flood frequency option

The *flood frequency* option allows users to optimise a set of hydrographs for different return periods. It was agreed at the start-up meeting that, for maximum flexibility, users will be required to import a separate FSU flood hydrograph for each return period (rather than simply a set of peak flows which would be used to scale a single hydrograph shape).

IBIDEM allows up to seven return periods to be analysed at once. A separate pair of Tp and SPR values is fitted for each return period, using the method described in Section 3. Display of the results is described in Section 5.2.1.

4.2 Sensitivity to storm duration

This option, and the others described below, are made available once IBIDEM has performed the hydrograph fit for a single return period. The fitted values of Tp and SPR are retained (i.e. no further optimisation is carried out) and the FSR rainfall-runoff method is re-run with a variety of different storm durations (five in all). The volume of the flood hydrograph will increase as the storm duration increases.

Default durations are set to those suggested in the specification, i.e. 0.5D, √0.5D, D, √2D and 2D where D is the duration resulting from the Tp value found in the optimisation. The user can change the durations if desired.

This option may allow IBIDEM to provide a useful route to generating realistic hydrograph shapes for inputs to river models, for example in situations where a more prolonged hydrograph is required as an input in order to generate a T-year flood further down the river system.

Display of the results is described in Section 5.2.1.

4.3 Sensitivity to model parameters

This option was suggested in our tender. It allows the user to re-run the rainfall-runoff method (after the initial optimisation stage) with altered values for Tp or SPR or both parameters. If Tp is altered, storm duration is automatically updated. If SPR is altered, PR is updated. Other settings remain unchanged.

The option allows users to investigate possible impacts of land use change, by adjusting Tp or SPR to represent "before" and "after" catchment conditions, where the user trusts the FSR rainfall-runoff method to represent a particular land-use change (such as agricultural drainage or tree planting).

Display of the results is described in Section 5.2.1.

4.4 Sensitivity to changes in urbanisation

This is another option that was suggested in our tender. It allows the user to re-run the rainfall-runoff method (after the initial optimisation stage) with an altered value of URBEXT. IBIDEM calculates revised values for Tp and PR to reflect the change to URBEXT, as follows.

The first step is to convert the revised URBEXT to URBAN (i.e. the FSR catchment characteristic) using Equation A1.2 in the specification, i.e.

$$URBAN_{FSR} = 1.567\ URBEXT \qquad (4.1)$$

In the FSR rainfall-runoff method method, URBAN affects Tp, PR and the choice of design event package (winter or summer).

The effect on PR is straightforward: IBIDEM calculates a new PR from SPR using the urban adjustment equation given in Section 3.2.

The choice of design event package is set manually by the user as in the main part of IBIDEM. It is not appropriate to set this automatically, otherwise it would be possible for a small increase in URBEXT (taking it over the threshold that defines an urban catchment) to result in a change from winter to summer design event, with potentially a large change in the flood hydrograph. Therefore IBIDEM retains the user's choice of design event package rather than updating it.

The effect on Tp is rather more complicated. Tp will have been set during the optimisation. Now it is necessary to change it to take account of the revised value of URBAN. The way IBIDEM does this is to use part of the Tp(0) equation given in Flood Studies Supplementary Report 16. Tp(0) is given as various other quantities multiplied by $(1+\text{URBAN})^{-2.2}$. And Tp = Tp(0) + ΔT/2.

To calculate the revised Tp , which we will call Tp_2, we need:

- the original URBAN_1 supplied at the start
- the revised value URBAN_2 provided by the user
- the original time to peak, Tp_1, from the optimisation
- the data interval, ΔT

The first step is to convert Tp_1 to $\text{Tp}(0)_1$:

$$\text{Tp}(0)_1 = \text{Tp}_1 - \Delta T/2 \tag{4.2}$$

Then we adjust $\text{Tp}(0)_1$ to take account of the change in URBAN:

$$\text{Tp}(0)_2 = \text{Tp}(0)_1 \frac{(1+URBAN_2)^{-\ .2}}{(1+URBAN_1)^{-\ .2}} \tag{4.3}$$

Finally we convert back to the new value of time to peak:

$$\text{Tp}_2 = \text{Tp}(0)_2 + \Delta T/2 \tag{4.4}$$

This option allows users to investigate impacts of urban development on design flood hydrographs and peak flows.

Display of the results is described in Section 5.2.1.

5 INPUTS AND OUTPUTS

5.1 Inputs

The software requires the following inputs in all cases:

- Catchment descriptors AREA, SAAR and URBEXT, which the user types in on the first screen. URBEXT needs to be expressed as a proportion (i.e. in the range 0 to 1), not as a percentage.
- Hydrograph derived from FSU procedures, supplied as a CSV file giving pairs of time and flow values.
- Rainfall frequency data from FSU procedures, supplied as a CSV file giving a table of design rainfall depths at an average point in the catchment for a large set of return periods and durations.
- Return period corresponding to the hydrograph (default 2 years).
- Threshold flow to be used in fitting, expressed as a percentage of the peak flow (default 50%).

These data requirements are validated during the input process and the user is notified if any of the data are not included. In particular, the user is warned in two cases:

- If the baseflow is higher than any flow value on the imported hydrograph (otherwise the response element of the hydrograph will be negative). In this case the user needs to either import a hydrograph with a higher minimum flow (e.g. removing the first or last few values) or reduce the baseflow.
- If the threshold flow is lower than any flow value on the imported hydrograph (otherwise it will not be possible to calculate a hydrograph width at the threshold flow). In this case the user needs to either import a hydrograph with a lower starting or ending flow or raise the threshold flow used for the fitting.

Various other inputs are required for some of the optional functionality, i.e.:

For the flood frequency option:

- Hydrographs for multiple return periods.

For the option to vary baseflow:

- Value for baseflow.

For the sensitivity to model parameters option

- New value for Tp or SPR or both

For the sensitivity to changes in urbanisation option

- New value for URBEXT

5.2 Outputs

5.2.1 Graphical display

IBIDEM provides a graphical display of the hydrograph fit, showing the input FSU hydrograph, the fitted FSR hydrograph and the threshold flow used for fitting. The two hydrographs are aligned so that they peak at the same time. An example is shown in Figure 5-1.

When the **flood frequency option** is selected, the user can choose which return period to display (one at a time is allowed). Alternatively, it is possible to display a graph showing how various variables (peak flow, percentage runoff, SPR, Tp, rainfall depth or runoff volume) change with return period. The user can select one variable to plot at a time (Figure 5-2).

When the **sensitivity to storm duration option** is selected, IBIDEM can plot either a graph showing multiple hydrographs (one for each duration, plus the input FSU hydrograph) (Figure 5-3) or a graph showing how variables (peak flow, percentage runoff, rainfall depth or runoff volume) change with storm duration (Figure 5-4). The user can select one variable to plot at a time. This provides a straightforward way to identify the critical duration for a catchment, by plotting peak flow against duration.

When the **sensitivity to model parameters or urbanisation options** are selected, IBIDEM plots the imported FSU hydrograph, the original fitted FSR hydrograph and the altered FSR hydrograph resulting from the changed parameter(s) (Figure 5-5).

Various options are provided for graph layout and units:

- Hydrographs can be plotted with the *vertical axis* showing either % of peak flow (default) or m^3/s.
- Hydrographs can be plotted with the *time origin* either at the peak (default) or at the start of the FSR hydrograph.
- *Flow units* can be either m^3/s (default) or mm/hr. This option alters the units in the table of results as well as that for the graph.
- *Runoff volume units* can be either mm equivalent of catchment runoff (default) or m^3 or cumec-hours. The latter unit should be interpreted similarly to a person-day, i.e. it represents $1m^3/s$ sustained for one hour, i.e. $3600m^3$. This option alters the units in the table of results as well as that for the graph.
- The plots of variables versus return period can have a *horizontal axis* showing either Gumbel reduced variate, Logistic reduced variate or natural logarithm of return period, in addition to a subsidiary axis showing return period.

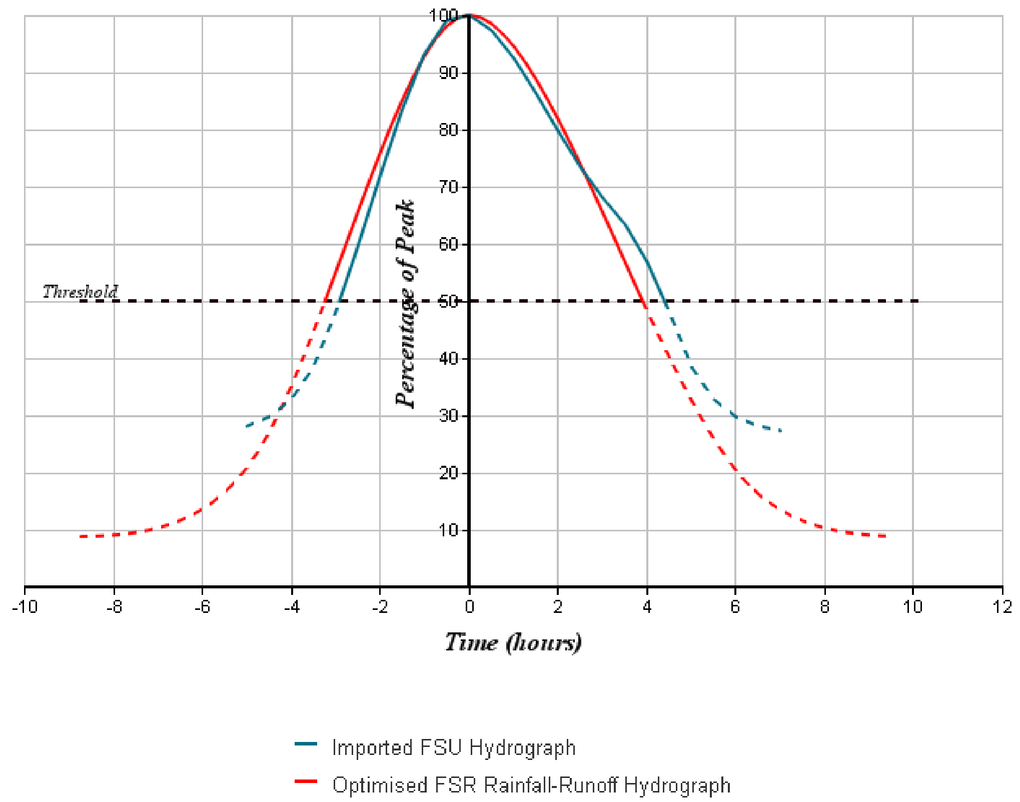


Figure 5-1: Display of fitted versus imported hydrograph

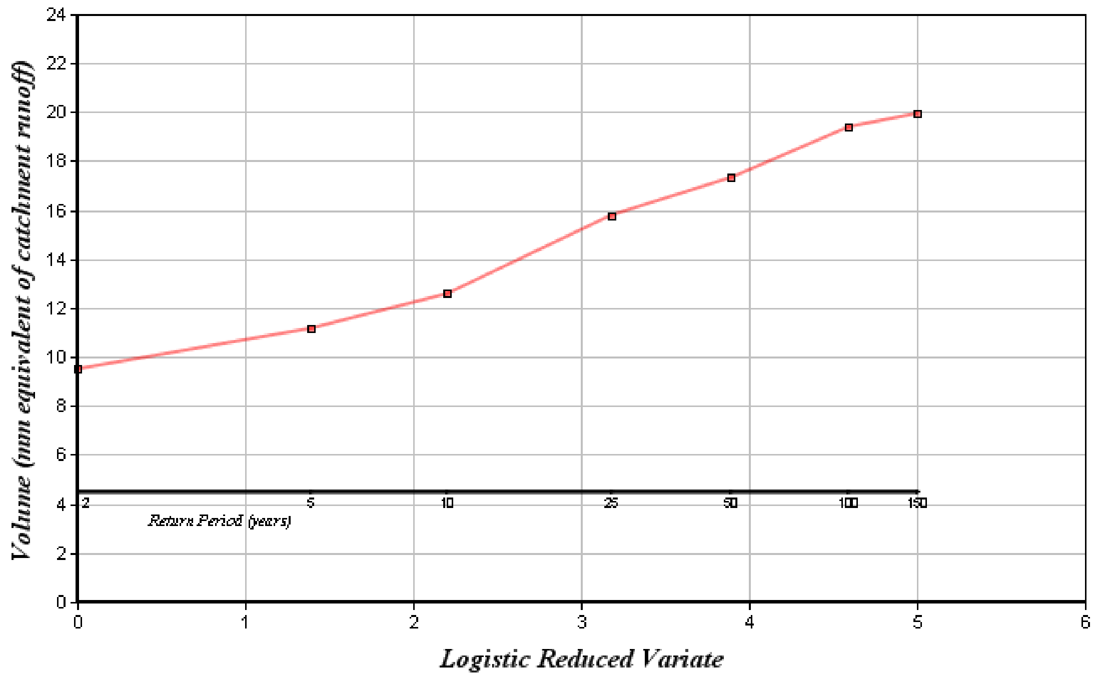


Figure 5-2: Display of how variables change with return period

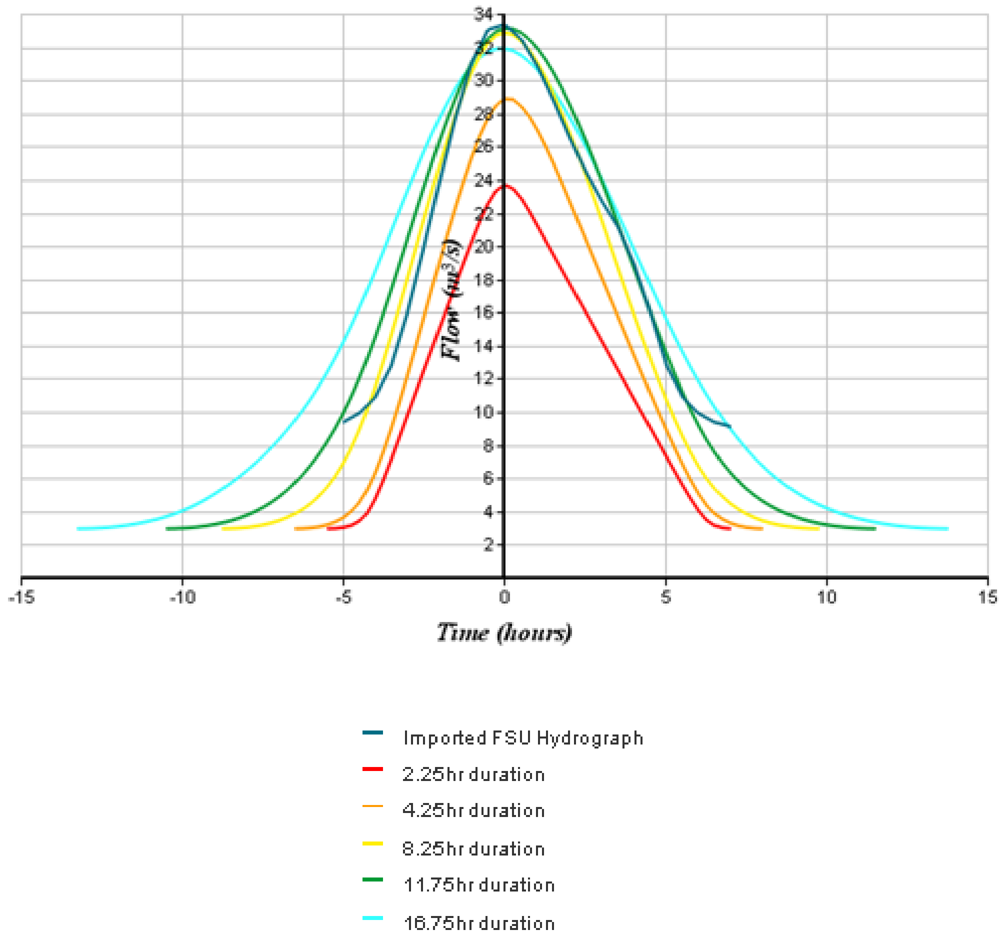


Figure 5-3: Display of hydrographs for multiple storm durations

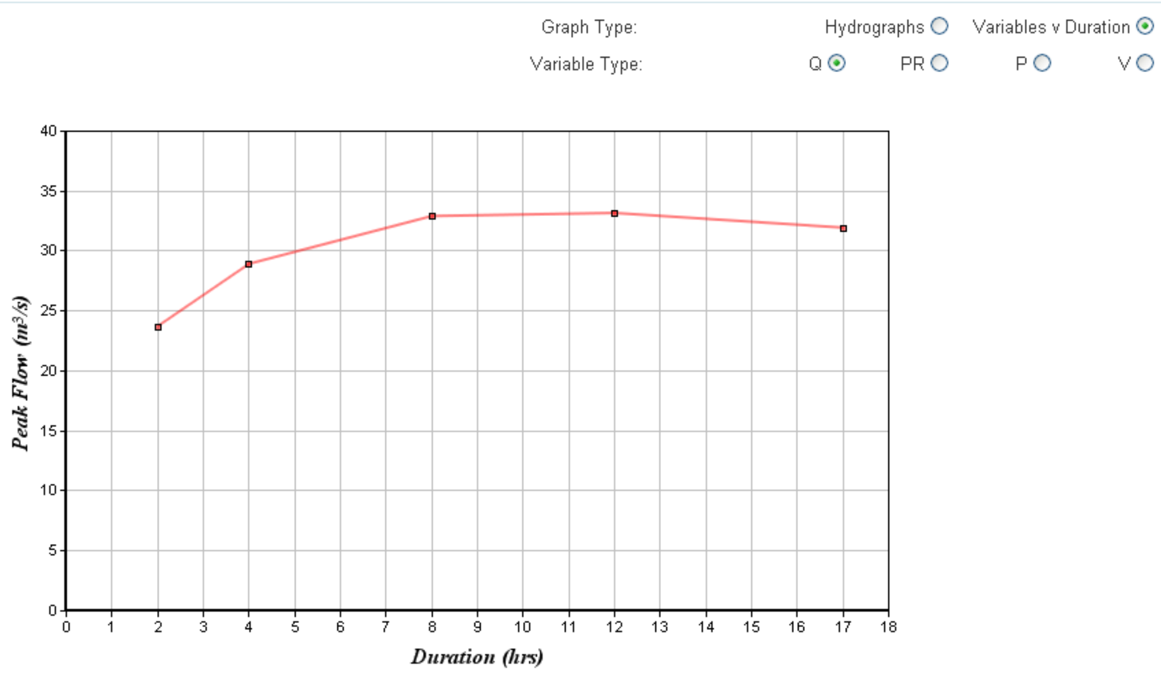


Figure 5-4: Display of how variables change with storm duration

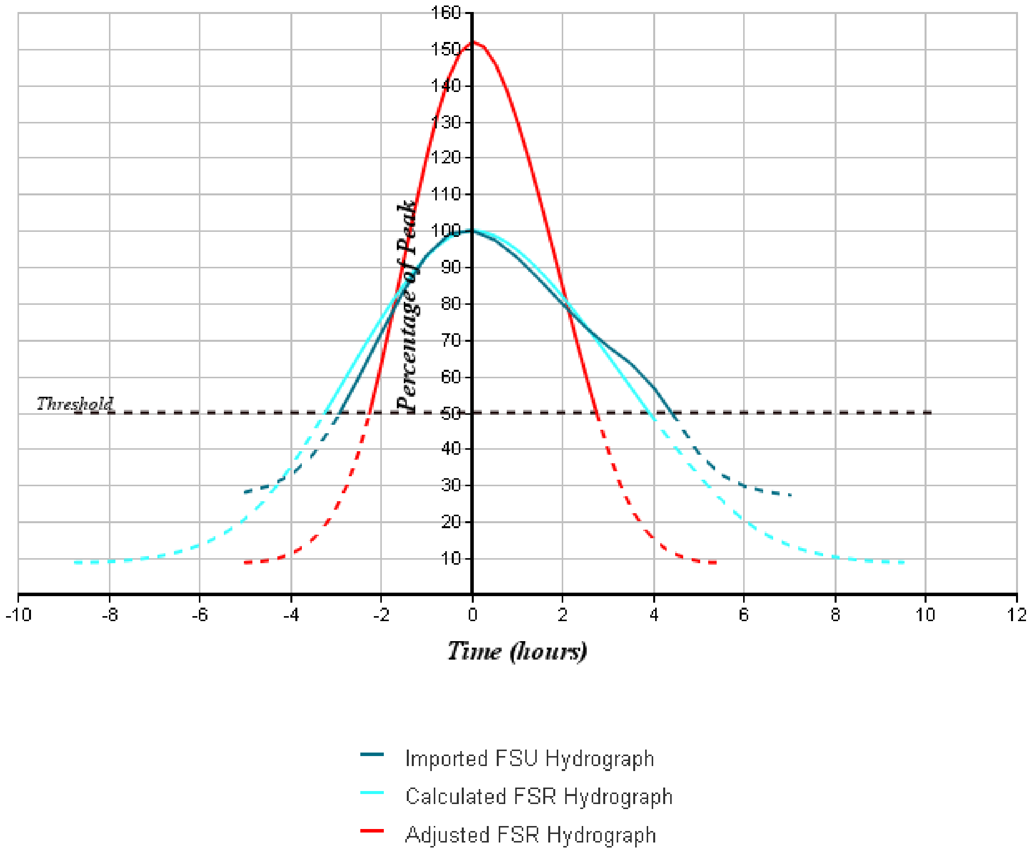


Figure 5-5: Display of sensitivity to an increase in URBEXT (from 0 to 0.20)

5.2.2 Goodness of fit measures

IBIDEM calculates two measures that indicate the goodness of fit of the two hydrographs, RMSE and Nash-Sutcliffe efficiency. They are calculated in quite different ways:

- RMSE is calculated as part of the fitting. It is the root mean square error in terms of hydrograph width (measured in hours) for the upper portion of the hydrograph over which the fitting was carried out. It indicates how well the hydrographs match in terms of width. The RMSE value output by IBIDEM should always be the minimum possible value given the shape of the input hydrograph and the family of possible shapes that the FSR rainfall-runoff hydrograph can take.
- The Nash-Sutcliffe efficiency coefficient, which is dimensionless, is calculated in the vertical (flow) direction. It is a measure of the goodness of fit in terms of flow over the entire duration of the imported FSU hydrograph. Values closer to 1 indicate a better fit. Negative values indicate that a better fit could be achieved using the mean flow. This statistic is calculated independently of the fitting done by IBIDEM, and so it will usually not take the minimum possible value.

The Nash-Sutcliffe efficiency (NSE) needs to be interpreted carefully. For example, the fitted hydrograph shown in Figure 5-6 has a NSE of -0.70, indicating that the fit is poorer than what could be achieved using the mean flow. This is because the receding limb of the FSR hydrograph is much steeper after the inflection point at 4 hours on the imported FSU hydrograph, and there is a long period after that time when the FSR hydrograph is much lower than the FSU hydrograph. The NSE gives no special weight to the fit around the peak, which is quite good in the example below. If the imported hydrograph is cut off earlier (7 hours after the peak), the NSE increases dramatically, to +0.70 (Figure 5-7).

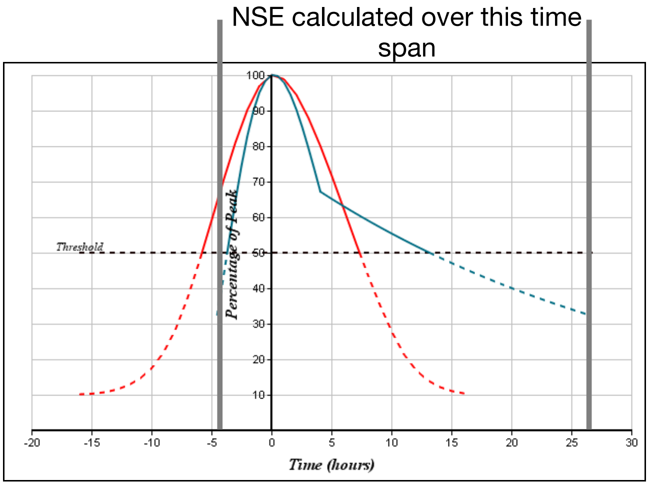


Figure 5-6: Example hydrograph (red) fitted to gamma curve plus exponential recession (turquoise)

Nash-Sutcliffe efficiency: -0.70

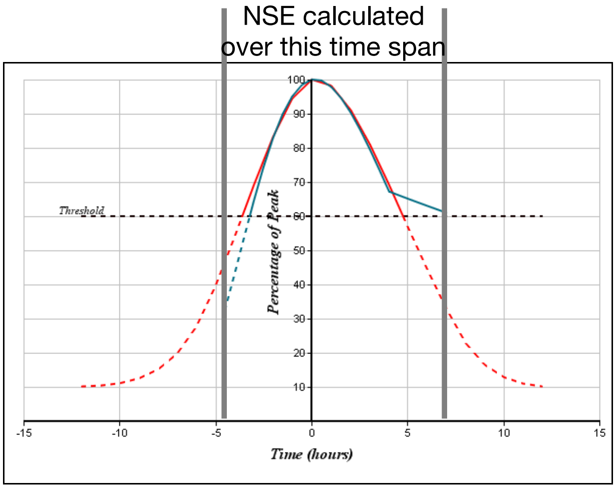


Figure 5-7: Same example with imported hydrograph cut off 7 hours after peak

Nash-Sutcliffe efficiency: +0.70

5.2.3 Tabular display

Below the graph, IBIDEM shows a table of parameter values and other variables (Figure 5-8). After the hydrograph fitting is carried out, the variables shown are: flow return period, rainfall return period, baseflow (BF), fitted Tp, fitted SPR, PR (calculated from SPR), timestep, storm duration (calculated from Tp and SAAR), rainfall depth (calculated from storm duration and return period), peak flow (taken from the *input* hydrograph), runoff volume, RMSE and Nash-Sutcliffe efficiency.

Slightly different versions of the table are shown after the user selects options such as sensitivity to storm duration. For example, it is not appropriate to show the goodness of fit statistics within these options. The order of the rows in each version of the table stays the same, but to help the user interpret the table, the row containing the variable that the user has changed (between columns) is highlighted. For example, in Figure 5-8, the flow return period is highlighted. Any rows containing variables that never change between columns are shown in grey. For example, baseflow does not vary with return period so the baseflow row is shaded grey on Figure 5-8.

Flow Return Period (yrs)	2	5
Rainfall Return Period (yrs)	2	8
BF (m^3/s)	2.94	2.94
Tp (hrs)	4.06	4.06
SPR	28.1	26.0
PR	27.6	25.5
Timestep (hrs)	0.25	0.25
Duration (hrs)	8.25	8.25
Rainfall Depth (mm)	29.6	39.0
Peak Flow (m^3/s)	33.37	40.04
Volume (mm equivalent of catchment runoff)	9.52	11.17
RMSE (hrs)	0.20	0.20
Nash-Sutcliffe Efficiency	0.944	0.934

Figure 5-8: Example tabular display, showing results for two return periods

5.2.4 Export of results

The software allows export of a summary report in .csv format, including a record of the FSU and FSR hydrographs, catchment descriptors used in the calculations, fitted parameters and measures of the goodness-of-fit. A different version of the report is exported from within the “Sensitivity to storm duration” option.

5.3 Checks and validation of outputs

IBIDEM checks the outputs and provides error, warning or information messages when necessary. A list of the checks made is given below.

Table 5-1: Checks and outputs

Criterion	Status	Comment	Notes
SPR ≤ 0	Error	Inferred SPR is not positive	This could happen, for example, when the peak of the input hydrograph is unrealistically low and the catchment is urbanised. After the urban component of the PR is calculated by IBIDEM, it can be necessary to use a negative SPR in order to match the input peak flow. The most likely cause will be that the FSU peak flow is too low, for example due to failure to incorporate an adequate urban adjustment in QMED. Alternatively, the catchment may not be well represented by the structure of the FSR rainfall-runoff model or the composition of the design event used as the input to the model.
0<SPR≤10	Warning	Inferred SPR is unusually low	This may be valid if the catchment is highly permeable. But it could otherwise be caused by the problems mentioned above, e.g. an unrealistically low input peak flow.

Criterion	Status	Comment	Notes
10<SPR≤25	Information	Inferred SPR implies a notably permeable catchment	
50<SPR≤60	Information	Inferred SPR implies a notably impermeable catchment	
60<SPR≤100	Warning	Inferred SPR is unusually high	This may be valid if the catchment is extremely impermeable. But it could otherwise be caused by an unrealistically high input peak flow.
SPR>100	Error	Inferred SPR is more than 100%	This could happen when the peak of the input hydrograph is unrealistically high given the nature and size of the catchment.
Tp≤0	Error	Inferred Tp is less than zero	This cannot happen given the procedure used to determine Tp.
PR ≤ 0	Error	Inferred PR is not positive	This should not happen. PR is calculated using Equation 3.4, which should not yield a negative result as all the other variables in the equation can only take positive values.
75<PR≤100	Warning	Inferred PR is unusually high	
PR>100	Error	Inferred PR is more than 100%	This would typically happen if SPR>100.

The specification also called for checks to be made on the inferred baseflow. These are not necessary because baseflow is not inferred by IBIDEM; it is calculated or input by the user before the optimisation is carried out.

6 TESTING IBIDEM

6.1 Choice of test sites

IBIDEM has been tested on a variety of catchments using a variety of FSU hydrograph shapes, including a mixture of empirical hydrographs (on gauged catchments) and synthetic ones (on ungauged catchments).

The test catchments, shown on Figure 6-1, are:

1. Suir at Caher Park – large rural catchment (1602km^2) with flow data available (station 16009).
2. Owenboy at Ballea – small to medium-sized rural catchment (103km^2) with flow data available (station 19001).
3. Lagan at Aclint - medium-sized rural catchment (144km^2) with flow data available (station 6026).
4. Anner River, tributary of Suir at Clonmel – medium to large-sized rural catchment (443km^2) with no flow data.
5. Tributary of Tolka at Finglas – small urban catchment (8km^2) with no flow data.

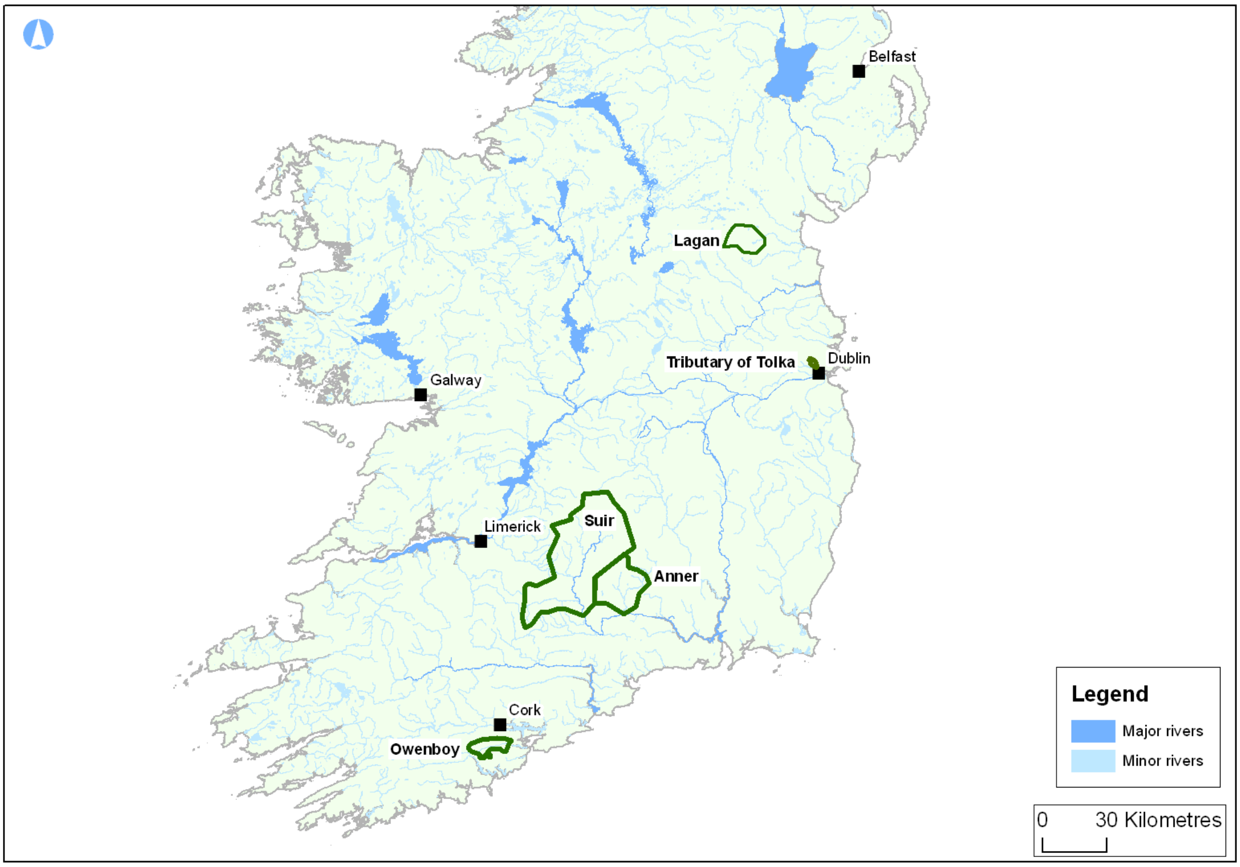


Figure 6-1: Location of test catchments

6.2 Methodology

6.2.1 Estimation of FSU hydrograph shapes

On the three gauged catchments (Suir, Owenboy and Lagan) hydrograph shapes were constructed using the width-averaging procedure developed by Archer *et al.* (1999)[3] and implemented in FSU WP3.1. The HWA software developed within WP3.1 was used to derive characteristic hydrograph shapes. All annual maximum flood events during the period of record were analysed to obtain median widths at percentiles of the peak flow.

On the ungauged catchments, characteristic hydrograph shapes were derived using both of the approaches developed in WP3.1: the parametric function (gamma curve plus exponential recession), and the non-parametric method which involves specifying the width of the hydrograph at the 75 and 50 percentiles of the peak flow and an eccentricity to indicate the skewness of the hydrograph, then fitting a parabolic curve.

The equations for estimating the required descriptors and deriving the hydrographs were taken from extracts from the draft final report on WP3.1 (January 2009). Catchment descriptors were taken from the information supplied by OPW in January and March 2009, apart from BFI which was not available when needed. BFI values were approximated from nearby gauging stations instead. The descriptors are shown in Table 6-1.

Table 6-1: Catchment descriptors and hydrograph shape descriptors

Variable	River Anner	Tributary of Tolka
Catchment descriptors		
BFI	0.51	0.52
Note on BFI	Obtained from nearby gauging station 15001	Obtained from nearby gauging station 8005
FARL	0.999	1
ALLUV	0.047	0
ARTDRAIN	0	0.014
S1085 (m/km)	3.4	16.1
Curve descriptors for the gamma hydrograph		
n (shape parameter of gamma curve)	7.35	7.23
Tr (hours) (rise time of gamma curve)	9.68	12.62
c (hours) (recession constant of exponential curve)	30.80	32.77
Width descriptors for the parabolic hydrograph		
W75 (hours)	4.18	4.90
W50 (hours)	7.03	7.57
s (eccentricity)	0.4	0.4

The draft report on WP3.1 offers several options for defining the shape of the characteristic flood hydrograph using width descriptors. We used option (d), *Application of an FEH-type asymmetric parabolic equation fitting both* W_{50} and W_{75}. This allows more flexibility in the hydrograph shape than some other options, while matching both the W_{50} and W_{75} widths produced by the respective regression equations. The procedures for constructing both types of hydrograph were implemented using a spreadsheet.

Graphs of the resulting hydrograph shapes are shown below in Figures 6.2 to 6.8.

[3] Archer, D., Foster, M., Faulkner, D. and Mawdsley, J., 2000. The synthesis of design flood hydrographs. Proc. *Flooding: risks and reactions*. CIWEM/ICE Conference, London, October 5, 2000, pp. 45-57.

6.2.2 Estimation of FSU peak flows

As stated in the specification, it is possible to develop IBIDEM using trial estimates of flood frequency rather than using the full procedures developed in Work Packages 2.2 and 2.3. Peak flows have been estimated as follows:

QMED was estimated from annual maximum flows on the gauged catchments and from catchment descriptors at the ungauged sites. The catchment descriptor equation used was the one given in the July 2008 progress report on WP2.3. This differs slightly from the version given in the 090312 short progress report, which was provided after the flood estimates had been calculated. The revised equation was applied later for comparison, and was found to give estimates within 10% of the July 2008 equation.

On the urbanised catchment (tributary of the Tolka at Finglas), QMED was adjusted for urbanisation using the adjustment factor give in the note on urban adjustment for QMED estimates provided by OPW on 24 March 2009. Please note that this is different from the final urban adjustment procedure used in the FSU.

Design flows for other return periods were estimated by scaling QMED using the FSR regional growth curve for Ireland (re-scaled by dividing by the growth factor for the 2-year flood so that QMED could be used as the index flood). A range of return periods was selected, although not all were tested for all five catchments.

The resulting design flows are given in Table 6-2.

Table 6-2: Design flows for the five test catchments

Return period (years)	2	5	50	100	200
AEP (%)	50	20	2	1	0.5
Catchment	Design flows in m^3/s				
Suir at Caher Park	162	204	303	334	366
Owenboy at Ballea	15.4	19.4	28.8	31.7	34.7
Lagan at Aclint	12.9	16.3	24.2	26.6	29.2
Anner at Clonmel	61.5	77.6	115	127	139
Tributary of Tolka at Finglas	1.62	2.05	3.03	3.34	3.66

6.2.3 Compilation of rainfall depth-duration frequency tables

When IBIDEM is applied in practice, it will require a table of design rainfall values for a typical point in the catchment (Section 3.2). This information is not yet available and so IBIDEM was tested by inputting a table of design rainfall depths for a single grid point located close to the centre of each of the five test catchments. It should be stressed that this approach will not be suitable for real applications of IBIDEM, particularly on large catchments where there is potential for a single grid point to be unrepresentative of the catchment as a whole. The rainfall depths were obtained from the CSV file containing design rainfalls provided by Met Éireann.

6.2.4 Procedure used for testing

Catchment testing

The use of several catchments has enabled the testing of variations in catchment properties such as AREA, SAAR and URBEXT. The catchment descriptors are shown in Table 6-3.

Table 6-3: Input variables for the five test catchments

Catchment	AREA (km^2)	SAAR (mm)	URBEXT (as a proportion)	Hydrographs Return periods: 2, 5, 50, 100 & 200 years	Coordinate for rainfall DDF data	
					East	North
Suir at Caher Park	1602	1079	0.009	Empirical	200000	146000
Owenboy at Ballea	106	1176	0.018	Empirical	162000	62000
Lagan at Aclint	144	1072	0.007	Empirical	310000	224000
Anner at Clonmel	443	986	0.003	Synthetic	224000	134000
Tributary of Tolka at Finglas	8	734	0.527	Synthetic	321000	240000

Variable testing

There are many variables and combinations of variables within IBIDEM. To thoroughly test that IBIDEM functions appropriately each catchment was tested over a range of realistic (expected through to extreme) and unrealistic input variables.

The variables tested include:

- Return period/s (2 to 200 years)
- Threshold for fitting (10 to 99%)
- Urbanisation (0.001 to 1)
- Storm duration (1.75 to 14.75 hours)
- Time to peak (3 to 30 hours)
- Standard percentage runoff (20 to 80%)

Functionality testing

IBIDEM was also assessed in terms of its operation. At each stage of testing the functionality and display of IBIDEM was checked, ensuring required areas were active and responsive, in the correct units and in a suitable layout and producing the appropriate results. On each new test page the following were tested:

- Validation, functionality and response
- Display and layout
- Results

In all, each catchment was tested over a range of variables and at each stage the full operation of IBIDEM was assessed, including the options to test sensitivity to storm duration, model parameters and urbanisation.

6.3 Results

An example of the hydrograph fit for each of the gauged catchments is shown below. All examples are for a return period of 100 years. Output statistics for all catchments are shown in Table 6-4.

6.3.1 Suir at Caher Park

The Suir at Caher Park used data from 54 flood events at gauging station 16009. For this catchment the calculated baseflow was 51.0 m^3/s. This is slightly lower than the minimum flow in the imported hydrograph, and it was necessary to reduce the baseflow to 50m^3/s after IBIDEM provided a warning message.

The fit of the calculated 100 year hydrograph for this catchment is shown in Figure 6-2. The FSU hydrograph has a rapid rising limb and a much slower recession limb. The FSR rainfall-runoff hydrograph, which can only take a limited range of shapes, cannot capture this shape. However, the method used in IBIDEM ensures that the widths of the two hydrographs are similar, on average, for flows above the threshold. The RMSE for this site is 12.7 hours. This is the highest RMSE for all the test sites (see Table 6-4) which is mainly due to the large size of the catchment (hence long duration of the flood hydrograph). The RMSE is also increased by the inflection points on the receding limb of the hydrograph, which means that the FSR hydrograph overestimates widths near the peak and underestimates widths for lower flows. The Nash-Sutcliffe efficiency is 0.50, indicating a moderately good fit in terms of flow.

The fitted time to peak is 52.8 hours and the SPR is 36.7%. Both these values seem reasonable for this large catchment of moderate permeability (BFI is 0.63).

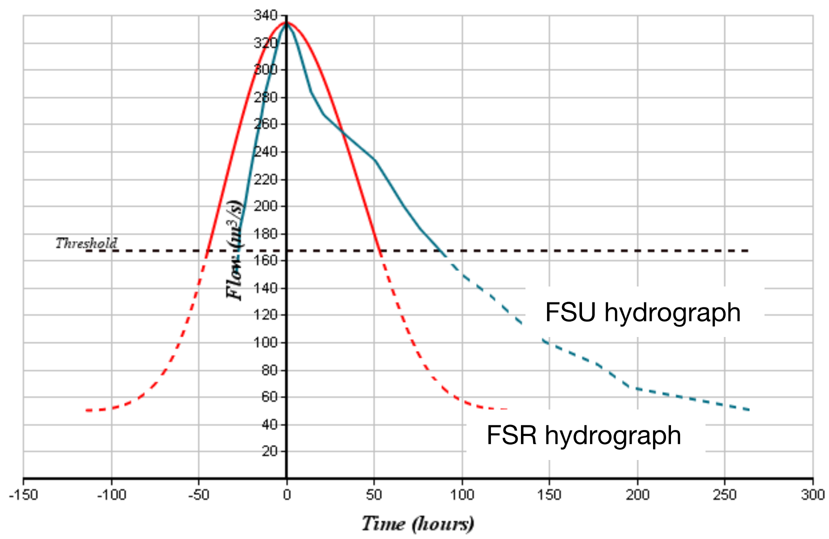


Figure 6-2: Suir at Caher Park 100 year hydrograph fit

6.3.2 Owenboy at Ballea

The Owenboy at Ballea catchment used data from 35 flood events at gauging station 19001. The fit of the calculated 100 year hydrograph for this catchment is shown in Figure 6-3. As at Caher Park, the FSU hydrograph is more skewed than the FSR one (i.e. it rises more rapidly and falls more slowly).

The RMSE for this site is 6.1 hours. The Nash-Sutcliffe efficiency is -0.48. This low value is due to the fact that the statistic is calculated as an average over the entire duration of the FSU hydrograph, even after the end of the plotted part of the FSR hydrograph (which is extended as a constant baseflow rate for the calculation). For times between 40 and 140 hours, the FSR flow is much lower than the FSU flow, hence the Nash-Sutcliffe efficiency reports a poor fit. The statistic could be improved by entering a higher value for baseflow, or cutting off the FSU hydrograph earlier.

The fitted time to peak is 31.1 hours and the SPR is 29.9%. These values seem reasonable for this moderate-sized catchment of moderate permeability (BFI is 0.64), although the Tp is perhaps rather long, as can be seen from the hydrograph plot. However, a shorter Tp would give a shorter duration hydrograph and hence a worse fit in terms of hydrograph widths.

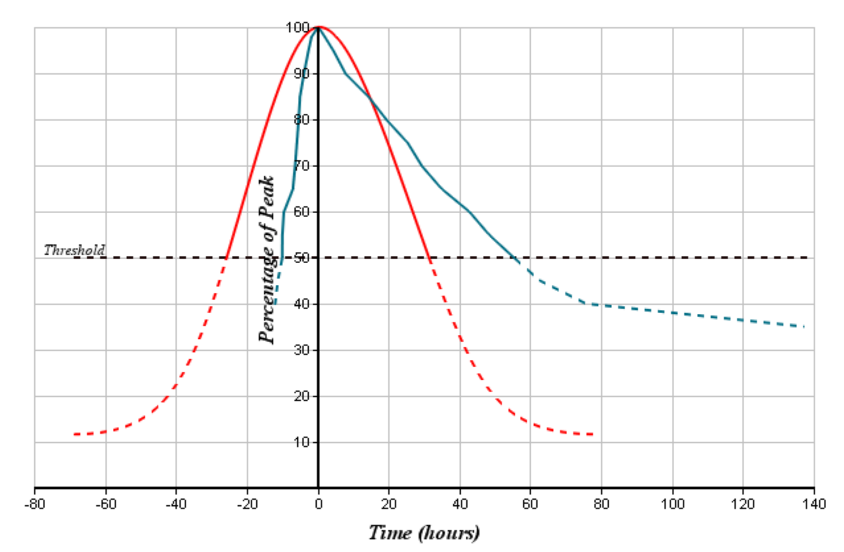


Figure 6-3: Owenboy at Ballea 100 year hydrograph fit

6.3.3 Lagan at Aclint

The Lagan at Aclint used data from 31 flood events at gauging station 6026.

For this catchment the threshold of 50% (default) triggered the following warning "Threshold flow is less than 100 yr input hydrograph start/end values, please adjust". The threshold was increased to 70%. The FSU hydrograph starts at a relatively high flow (see Figure 6-5) because the shape of the empirical hydrograph produced by the HWA software has a "time reversal" on the rising limb between 70 and 75% of the peak flow (see Figure 6-4). The fitting method used in IBIDEM can cope with such reversals (see Figure 6-6), but most users are unlikely to regard it as sensible to import a hydrograph in which time runs backwards. The time reversal was avoided by cutting off the input hydrograph 40 hours before the peak.

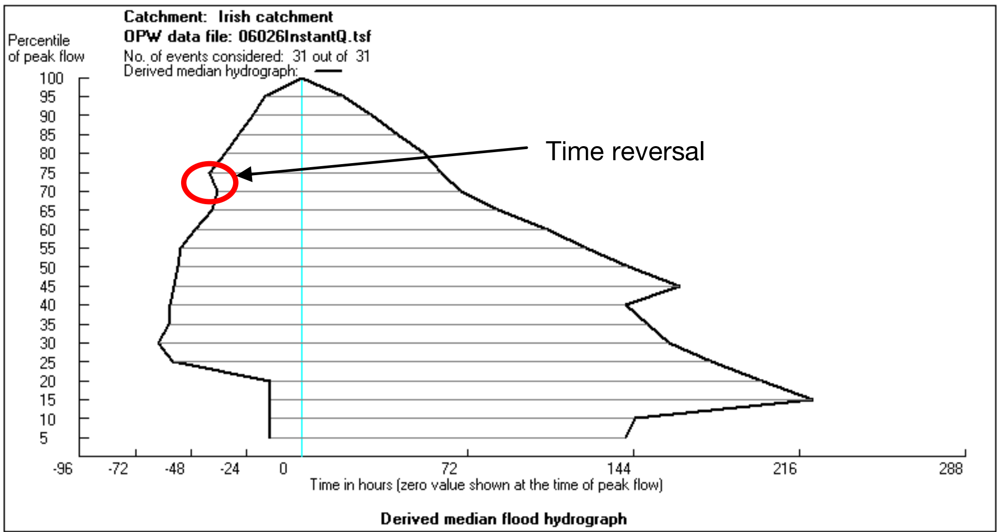


Figure 6-4: Lagan at Aclint – derived median hydrograph from HWA software

The fit of the calculated 100 year hydrograph for this catchment is shown in Figure 6-5. IBIDEM gives a good fit to the rising and falling limbs of the FSU hydrograph, above the threshold value used for fitting. The RMSE is 11.6 hours and the Nash-Sutcliffe efficiency is 0.64, indicating a fairly good fit in terms of flow.

The fitted time to peak is 97.3 hours The time to peak is surprisingly long given the size of the catchment (144km^2). The relatively slow flood response may be partly due to the influence of several loughs in the catchment (FARL is 0.91).

The fitted SPR is 48.8%. The BFI for this catchment is 0.66, indicating a moderately permeable catchment. The fitted SPR value is surprisingly high for such a catchment. The high value of SPR can be (at least partly) explained by the long time to peak which tends to produce a subdued hydrograph with a relatively low peak. IBIDEM has therefore had to increase SPR to compensate, in order to ensure that the FSU peak flow is matched.

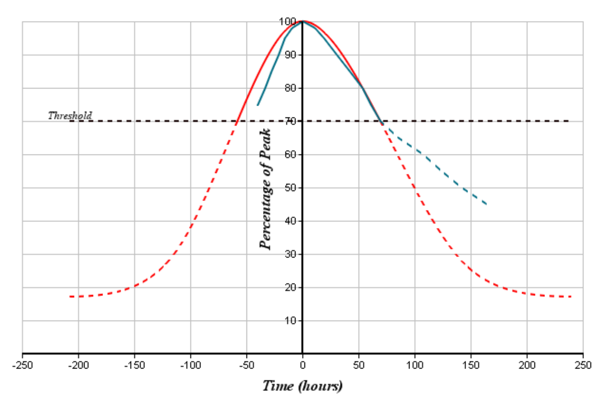


Figure 6-5: Lagan at Aclint 100 year hydrograph fit

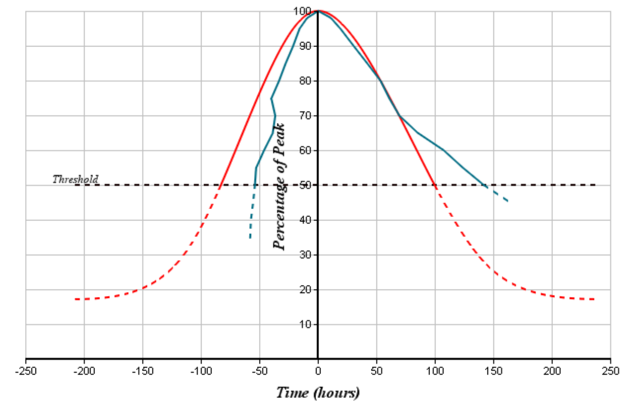


Figure 6-6: Lagan at Aclint 100 year hydrograph fit with time reversal in FSU hydrograph

6.3.4 Anner at Clonmel

Two sets of calculations were carried out for this catchment, one with the hydrograph shape derived from the parametric "curve descriptors" gamma and exponential functions and the other using the non-parametric "width descriptors" parabolic function. The resulting fitted hydrographs are shown in the figure below.

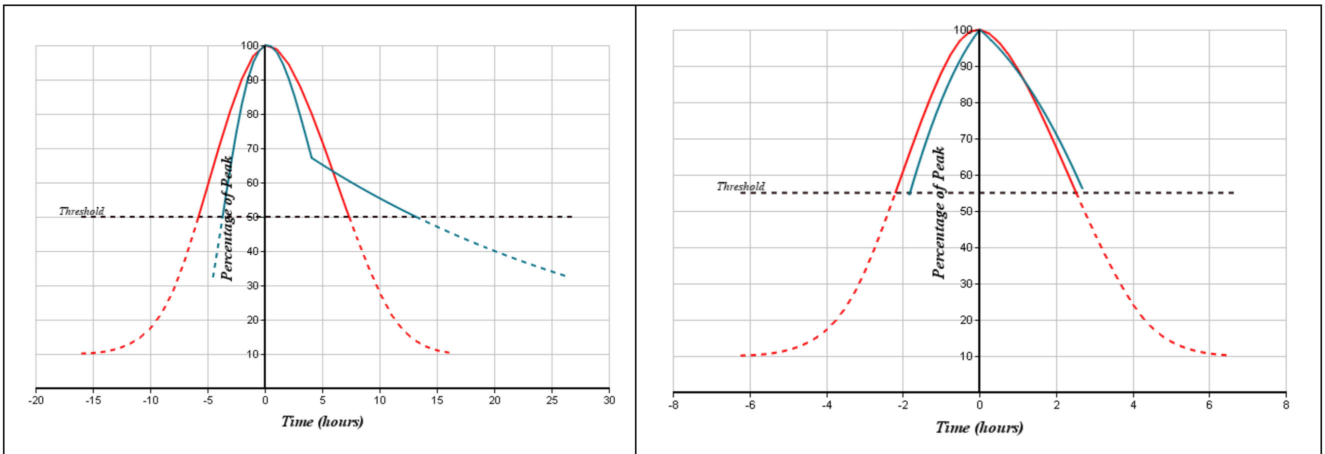
The gamma hydrograph is reasonably well fitted by the FSR hydrograph, the main difference being that the rainfall-runoff method cannot reproduce the sudden change of gradient on the falling limb which happens when the gamma function changes to an exponential curve. The RMSE is 1.9 hours and the Nash-Sutcliffe efficiency is -0.70. The latter statistic reflects the fact that the FSU flow is much higher than the FSR flow for much of the latter part of the hydrograph.

The FSR hydrograph gives a close fit to the parabolic function for flows about the threshold. The RMSE is 1.0 hours and the Nash-Sutcliffe efficiency is 0.85, indicating a close fit.

The fitted Tp is 2.8 hours for the parabolic hydrograph and 7.1 hours for the gamma hydrograph. These times to peak (particularly 2.8 hours) seem unusually short for this medium to large rural catchment (443km^2). Somewhat surprisingly, the regression equations that predict the hydrograph widths from catchment descriptors do not include any descriptors related to catchment size. For example, the width of the parabolic hydrograph is based on BFI, FARL, ALLUV, ARTDRAIN and S1085. It is possible that the hydrograph shapes produced by the methods developed in WP3.1 are too narrow for this catchment.

Fitted SPR values are 0.4% for the parabolic hydrograph and 2.3% for the gamma hydrograph. IBIDEM correctly warns that these values are suspiciously low. An SPR of 0.4% is almost certainly too low, because it implies virtually none of the storm rainfall becomes rapid response runoff. This small value is probably (at least partly) due to the need to compensate for the small values of Tp. IBIDEM has had to decrease SPR in order to ensure that the FSU peak flow is matched.

There are other possible explanations for the extremely low SPR values. One is that the SPR is very low because the peak of the input FSU hydrograph is unrealistically low given the nature of the catchment. Alternatively, the catchment may not be well represented by the structure of the FSR rainfall-runoff model or the composition of the design event used as the input to the model. It is also possible that rainfall characteristics of the catchment as a whole are not well represented by the single central point from which the rainfall DDF results were obtained. This can be checked by comparing the value of SAAR for the whole catchment (986mm) with the SAAR for a small catchment close to the point at which the DDF statistics were extracted (1060mm). These values are similar enough to suggest that the use of DDF statistics at a single point is probably not the main factor contributing to the low fitted SPR. The most likely explanation seems to be the need to compensate for the small value of Tp.



Gamma hydrograph	Parabolic hydrograph

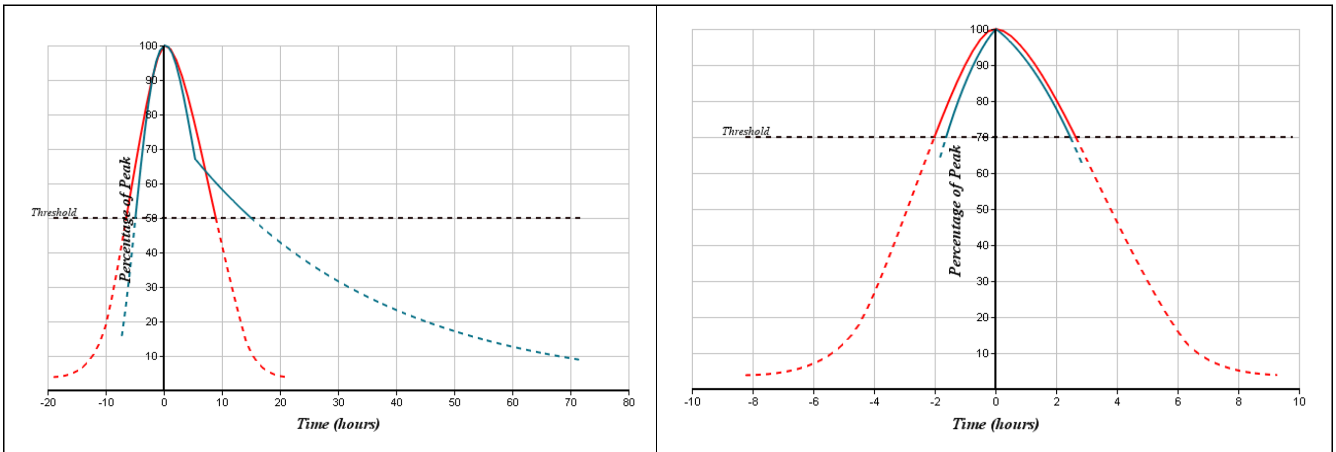
Figure 6-7: Anner at Clonmel 100 year hydrograph fit

6.3.5 Tolka at Finglas

As on the River Anner, two sets of calculations were carried out using the alternative hydrograph shapes developed by WP3.1.

Because this small catchment is heavily urbanised, the urban catchment design package was used within IBIDEM. This means that the 100-year return period rainfall depth was used to simulate the 100-year flood hydrograph, and the 50% summer rainfall profile was adopted.

As on the River Anner, the fitted hydrograph matches the FSU shape fairly well for the gamma hydrograph and very closely for the parabolic hydrograph. RMSE and Nash-Sutcliffe efficiency values can be seen in Table 6-4 below.



Gamma hydrograph	Parabolic hydrograph

Figure 6-8: Tributary of Tolka at Finglas 100 year hydrograph fit

Fitted Tp values are 9.3 hours for the gamma hydrograph and 4.2 hours for the parabolic hydrograph. These seem suspiciously long for a small urban catchment. In fact they are longer than the fitted Tp values for the Anner catchment, which is over fifty times larger, as well as being much more rural. It is difficult to believe that the FSU hydrograph shapes are realistic.

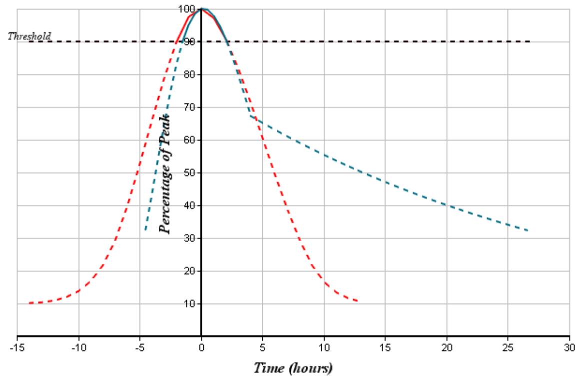
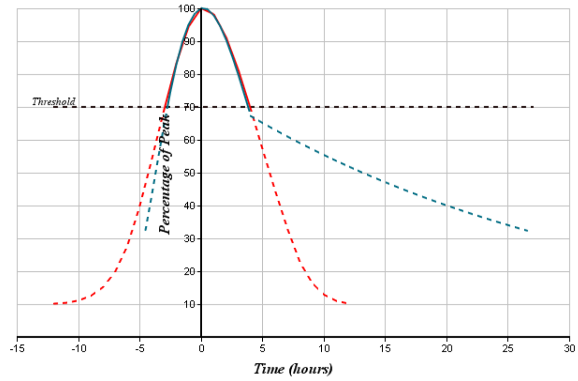
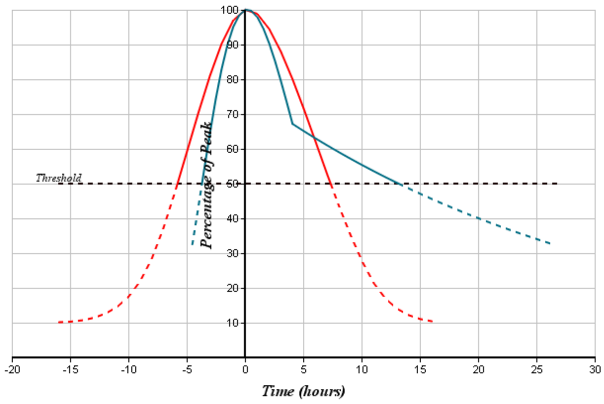
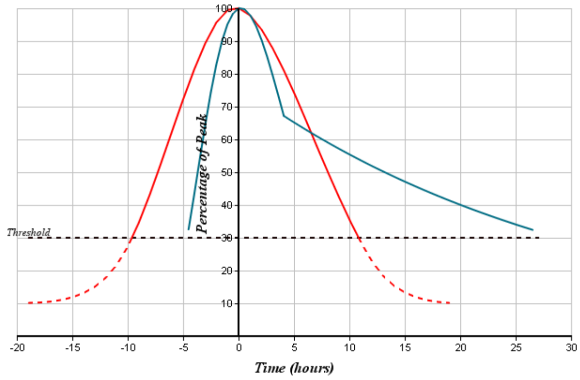
The fitted SPR value of 25% for the gamma hydrograph is considerably lower than the PR of 38%. This is due to the heavily urbanised nature of the catchment. The PR has been calculated from the peak flow of the input hydrograph (along with other parameters) and then converted to PR_{rural} by removing the urban adjustment, before calculating SPR. The fitted SPR for the parabolic hydrograph is 6.3% which is unusually low. SPR is lower for the parabolic hydrograph because Tp is lower.

Table 6-4: Summary of output results grid for the five test catchments, all for a flood return period of 100 years

Variable	Suir	Owenboy	Lagan	Anner		Tolka	
				Gamma	Parabolic	Gamma	Parabolic
Rainfall return period (years)	140	140	140	140	140	100	100
BF (m^3/s)	50	3.69	4.56	12.85	12.85	0.13	0.13
Tp (hours)	52.8	31.1	97.3	7.1	2.8	9.3	4.2
SPR	36.7	29.9	48.8	**2.3**	**0.4**	25.3	**6.3**
PR	46.8	40.2	60.7	10.9	6.2	38.1	22.1
Timestep (hours)	1	1	1	1	0.25	1	0.25
Storm duration (hours)	111	69	203	15	5.75	17	7.25
Rainfall depth (mm)	122.2	126.9	149.4	102.1	70.8	85.2	64.8
Peak flow (m^3/s)	334.0	31.7	26.6	126.9	126.9	3.3	3.3
Volume (mm equivalent of catchment runoff)	84.6	69.9	141.3	15.0	5.9	24.4	10.7
RMSE (hours)	12.68	6.09	11.58	1.88	1.02	1.69	0.48
Nash-Sutcliffe efficiency	0.499	-0.479	0.642	-0.697	0.847	0.033	0.875

6.4 Illustration of effect of fitting threshold

Tests were carried out with a wide range of thresholds. The effect of varying the threshold is illustrated below for the River Anner at Clonmel, using an input hydrograph constructed using the parametric “curve descriptors” gamma and exponential functions. Note that the threshold is shown as a horizontal line in each plot.

Threshold	Hydrograph plot	Fitting statistics
90%		RMSE 0.31 hr Nash-Sutcliffe -1.29 Close fit for the small portion of the hydrograph above the threshold.
70%		RMSE 0.19 hr Nash-Sutcliffe -1.42 Very close fit for the portion of the hydrograph above the threshold (hence low RMSE).
50%		RMSE 1.88 hr Nash-Sutcliffe -0.70 Increasingly wider fitted hydrograph due to wider input hydrograph for flows below the inflection point on the falling limb. RMSE is lower but Nash-Sutcliffe efficiency indicates better fit in terms of flow.
30%		RMSE 5.80 hr Nash-Sutcliffe -0.50 Continuation of the trends described above under 50%.

6.5 Discussion of test results

The tests that were carried out provided many opportunities to identify and sort out bugs in the software and make minor improvements. These have now been completed and the tests have been repeated to ensure that all the functionality performs as intended.

Some interesting results have emerged during the testing. In general, it appears that IBIDEM gives broadly sensible results on the three gauged catchments. The inferred Tp and SPR values were within expected ranges on the first two watercourses (Suir and Owenboy). On the River Lagan, the inferred Tp is rather longer than might be expected, and it appears possible that SPR has taken on a high value to compensate for this and ensure that the FSU peak flow is matched. However, the fitted parameter values are not totally unrealistic.

On the two ungauged catchments, some of the inferred parameters are less sensible. There are two particular problems, although they are inter-related:

- Tp values on the large rural Anner catchment are shorter than those on the small urban tributary of the River Tolka. This is not realistic, but IBIDEM is producing these results because it is fitting the widths of the supplied FSU hydrographs. The hydrograph shapes used in the tests have been derived using regression equations produced in WP3.1, which appear to take no account of catchment size. It is our suggestion that these equations should be further reviewed.
- SPR values are too small for the Anner and , in the case of the parabolic hydrograph shape, suspiciously small for the Tolka tributary. The SPR is derived within IBIDEM from several variables, including the peak of the input FSU hydrograph, the storm duration (which depends on Tp), the design rainfall depth, the catchment area and the urban extent. See Equation 3.5 for the full details. While errors in any of these are possible, the greatest uncertainty is likely to be associated with the peak of the input FSU hydrograph and the inferred Tp (which influences SPR via the storm duration, D, and also via the routing constant which depends on the ratio of D/Tp). In the case of the River Anner, the unrealistically low SPR value may be influenced by an unrealistically short Tp. In the case of the tributary of the Tolka, it is possible that the peak of the input FSU hydrograph is rather too low.

6.6 Comments on opportunities provided by IBIDEM

IBIDEM provides the opportunity to assess FSU outputs using a structured model of hydrograph formation. The test results discussed above have shown that IBIDEM can help in detecting hydrograph shapes or peak flows that appear to be inconsistent with the properties of the catchment.

However, users need to be aware that IBIDEM relies on the assumptions that are made in the FSR design event approach, which are not always appropriate. The design event method derives a flood hydrograph from a single combination of inputs (rainfall depth, rainfall duration, rainfall profile and catchment wetness index). This combination does not always result in a hydrograph peak of the required return period. The implication for IBIDEM is that the design event that it uses may not always be relevant to the supplied FSU design hydrograph.

A potential application of IBIDEM is in estimating improved design hydrographs on urban catchments. FSU methods could be used to derive an as-rural hydrograph (i.e. not applying the urban adjustment for QMED). The hydrograph would then be imported to IBIDEM, with URBEXT set to zero. After carrying out the fitting, the user would select the option to test sensitivity to urbanisation, and enter the correct value of URBEXT. The resulting adjusted hydrograph would provide an alternative estimate of peak flow for the catchment which could be compared with the flow estimated from the methods of WP2.3, incorporating the urban adjustment for QMED. Another advantage of applying IBIDEM on urban catchments would be that it adjusts the hydrograph shape to account for urbanisation. The procedures developed in WP3.1 do not allow any variation in hydrograph shape with URBEXT.

An example of this application on a very heavily urbanised catchment (tributary of Tolka at Finglas) is shown in Figure 6-9. The adjusted hydrograph has a peak flow over four times higher than the original one, and the time to peak is much shorter. The increase in peak flow is caused by two effects: the increase in percentage runoff and the decrease in time to peak (and consequently storm duration). This dramatic increase in peak flow is much higher than the factor of 2.54 given by the urban adjustment equation from WP2.3.

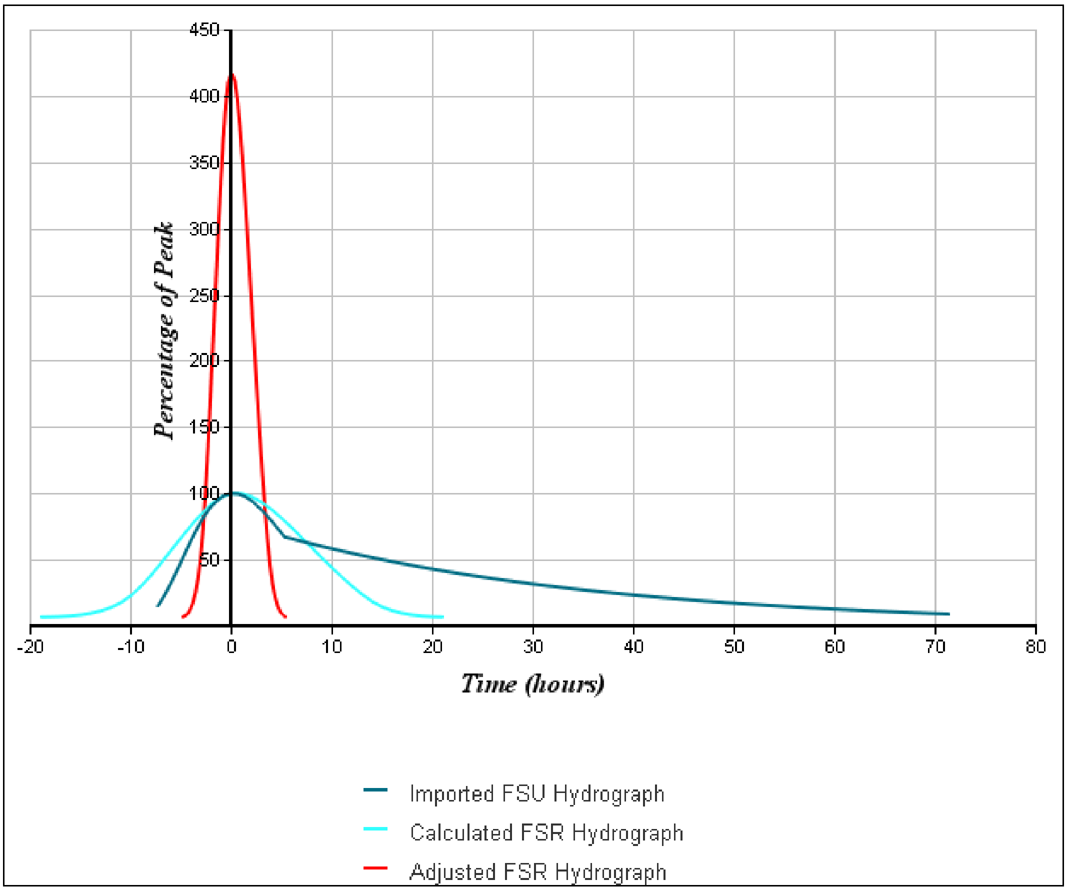


Figure 6-9: Illustration of urban adjustment to hydrograph for the Tolka tributary at Finglas

IBIDEM also has potential in deriving inflows for hydrodynamic river models, which often require hydrographs resulting from design storms with durations different from the critical duration of the sub-catchment. These hydrographs can be generated using the option to test sensitivity to storm duration. Hydrographs generated by IBIDEM are likely to be useful for flood storage and flood routing studies because they cover the full range of flows rather than just the upper part of the flood hydrograph which is what some of the methods developed in WP3.1 provide.

Other potential applications are for assessing the effects of *future* changes in urbanisation or other land use changes that can be tested by varying the parameters of the rainfall-runoff method.

7 DELIVERY AND SUPPORT OF THE SOFTWARE

7.1 Language and compatibility

The IBIDEM software is provided on a CD which accompanies this report. It is written in ASP.NET 2.0 (Active Server Pages). ASP.NET is an industry standard web application framework. The page layouts are designed using HTML (Hyper Text Markup Language), with the calculation processes being carried out on the web server using code written in VB.NET. Entered form values are validated with client-side JavaScript functions; in other words these functions are passed to the user's computer so that it is not necessary to communicate with the web server every time a data value is entered.

IBIDEM is a standalone series of pages that can be incorporated into another website on a server that supports ASP.NET 2.0. It is anticipated that IBIDEM will ultimately be incorporated into the website developed to implement the FSU procedures as a whole. JBA will provide the advice and support necessary for OPW or their contractor to incorporate IBIDEM in the FSU website.

7.2 Future alterations to the code

In the future OPW may want to make alterations to the code, or specify alterations to be carried out by contractors. This can be done by opening the website into Microsoft Visual Studio 2005 and updating the project as necessary.

Appendix A: - User guide

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USER GUIDE FOR IBIDEM

Purpose of IBIDEM

IBIDEM stands for Interactive Bridge Invoking the Design Event Method. It provides a bridge between the Flood Studies Update method of estimating a design flood hydrograph and the Flood Studies Report (FSR) design event method that FSU replaces.

In the FSU approach the design peak flow is estimated as the product of an index flood and a growth curve. The design hydrograph is then constructed around the peak flow by applying a hydrograph shape. There are two options for specifying a hydrograph shape:

1. An empirical approach, for sites where flow data is available, in which the hydrograph shape is built up using widths extracted from observed hydrographs for given percentages of the peak flow. This analysis can be carried out using the HWA software.
2. A synthetic approach for ungauged sites, with two variants: firstly a parametric function (gamma curve plus exponential recession) with parameters estimated from catchment descriptors, and secondly a non-parametric method which involves specifying the width of the hydrograph at the 75 and 50 percentiles of the peak flow and an eccentricity to indicate the skewness of the hydrograph. Where the full hydrograph is needed, the parametric “curve descriptors” function is recommended, with the non-parametric “width descriptors” method suggested for applications where only the upper part of the hydrograph is needed.

In the FSR approach, the design flood hydrograph is constructed as the output to the “unit hydrograph/losses” rainfall-runoff model. The FSR design event method combines four inputs: the duration, depth, and temporal profile of the rainfall event and the pre-event catchment wetness. Rainfall depths can be taken from the depth-duration-frequency model developed as part of the FSU research. The other inputs are set according to rules which reflect some of the general properties of the catchment and its climate.

The parameters of the rainfall-runoff model are the standard percentage runoff (SPR), the unit hydrograph time-to-peak (Tp) and the standardised baseflow, known as “average non-separated flow” (ANSF). In a standard application of the FSR approach, these are derived from hydrometric data or catchment characteristics. In contrast, IBIDEM calculates values for Tp and SPR so that the design hydrograph synthesised by the FSR method matches that produced by the FSU procedures.

The benefits of this approach include:

1. Synthesis of the complete flood hydrograph, rather than just the upper part which is provided by the empirical approach developed for the FSU. This may be useful in deriving inflows for hydrodynamic models and for flood storage studies.
2. Testing sensitivity of the flood hydrograph to storm duration, also helpful for river modelling.
3. Assessing whether the peak flow or hydrograph shape derived by FSU methods are realistic given the properties of the catchment. For example, if the fitted value of standard percentage runoff is unrealistically large or small then this should act as a warning sign.
4. Investigating how the flood hydrograph is affected by urbanisation or alterations in model parameters intended to represent land use changes.

Inputs needed

The inputs needed are:

- The catchment descriptors AREA (km^2), SAAR (mm) and URBEXT, typed in on the first screen. URBEXT needs to be expressed as a proportion (i.e. between 0 and 1), not as a percentage.
- A hydrograph derived from FSU procedures, supplied as a comma separated variable (.csv) file giving pairs of time (hours) and flow (m^3/s). Any time interval can be used, including an irregular one. IBIDEM can accept negative values of time, which will often be used due tot the definition of FSU hydrographs in relation to the time of the peak. An example of an input file for a half-hourly time interval is:

Time	Flow
0	9.39
0.5	9.93
1	10.94
1.5	12.82
2	15.98
2.5	19.83
3	23.92
3.5	27.84
etc.	

- The return period corresponding to the hydrograph.

It is also possible to import hydrographs for multiple return periods, up to seven. The user can specify the return periods.

- Rainfall frequency data from FSU procedures, supplied as a .csv file giving a table of design rainfall depths at an average point in the catchment for a large set of return periods and durations. The table has durations (0.25 - 600 hours) in rows and return periods (2 - 200 years) in columns. An example is shown below.

Durations (hours)

Return periods (years)

	2	5	10	20	30	50	100	150	200
0.25	8	9.7	10.9	12.2	12.9	13.9	15.4	16.3	17
0.5	10.4	12.6	14.2	15.8	16.7	18	19.9	21.1	22
1	13.4	16.4	18.4	20.5	21.7	23.4	25.9	27.4	28.6
2	17.4	21.2	23.8	26.5	28.2	30.4	33.5	35.6	37.1
3	20.3	24.7	27.8	30.9	32.8	35.3	39.1	41.4	43.1
4	22.6	27.6	30.9	34.4	36.5	39.4	43.5	46.1	48.1
6	26.3	32.1	36	40	42.5	45.8	50.7	53.7	55.9
9	30.7	37.3	41.9	46.6	49.5	53.4	59	62.5	65.1
12	34.1	41.6	46.7	51.9	55.2	59.4	65.7	69.6	72.6
18	39.8	48.4	54.4	60.5	64.2	69.2	76.5	81.1	84.5
24	44.3	53.9	60.6	67.3	71.5	77.1	85.2	90.3	94.1
48	54.6	65.2	72.4	79.6	84.1	90	98.5	103.8	107.7
72	63.6	75.1	82.8	90.6	95.3	101.6	110.5	116.1	120.2
96	71.8	84.2	92.4	100.7	105.7	112.2	121.6	127.5	131.8
144	87	100.8	109.9	119	124.5	131.7	141.9	148.2	152.9
192	101	116.2	126.1	135.9	141.8	149.5	160.5	167.3	172.2
240	114.3	130.7	141.3	151.8	158.1	166.3	178	185.1	190.4
288	127.2	144.6	155.9	167.1	173.7	182.4	194.7	202.2	207.7
384	151.8	171.3	183.8	196.1	203.4	212.9	226.3	234.5	240.5
480	175.5	196.8	210.4	223.8	231.7	242	256.4	265.2	271.6
600	204.4	227.7	242.6	257.1	265.8	276.9	292.5	301.9	308.8

Running IBIDEM

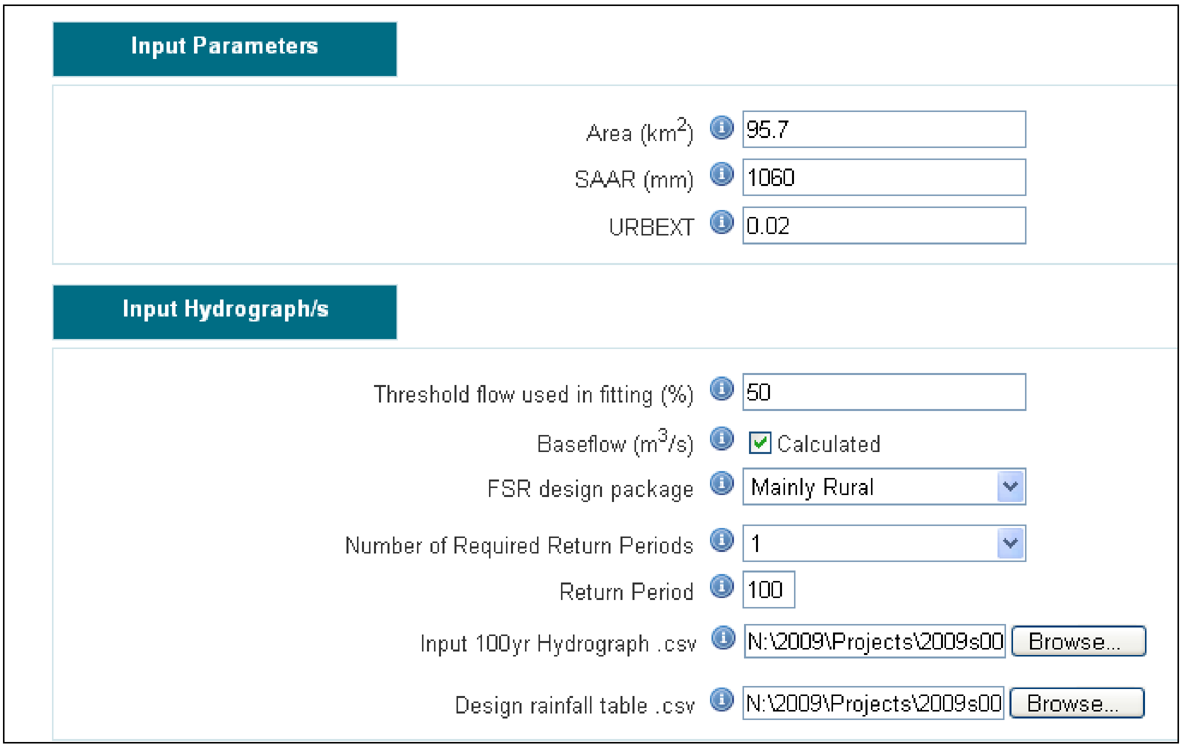
From the initial screen (below), the user enters the catchment descriptors and browses to files containing the input hydrograph(s) and design rainfall table.

It is possible to alter the baseflow and threshold flow used in fitting if desired. IBIDEM fits the FSR hydrograph to the FSU hydrograph for flows above a threshold value. By default this is set to 50% of the peak.

The FSR design package option allows the user to choose between the two design packages offered by the design event method:

- Mainly rural, i.e. flood return period is generally longer than the rainfall return period and design storm follows the 75% winter profile;
- Heavily urbanised, i.e. flood return period is equal to the rainfall return period and design storm follows the 50% summer profile.

In the Flood Studies Report, the heavily urbanised design package was recommended for catchments where the URBAN catchment descriptor exceeded 0.25. An URBAN value of 0.25 corresponds to an URBEXT of approximately 0.16.



To run IBIDEM, press Process

Error messages

If an error message along the lines of this one appears:

2 yr input hydrograph value(s) are less than 10.00m^3/s baseflow value, please adjust

it means that the imported hydrograph includes flow values that are less than the baseflow, which (by default) is calculated by IBIDEM using the FSR procedures. The user needs to either import a hydrograph with a higher minimum flow (e.g. removing the first or last few time steps in the hydrograph) or reduce the baseflow. The calculated value of baseflow can be overridden.

Another possible error message is:

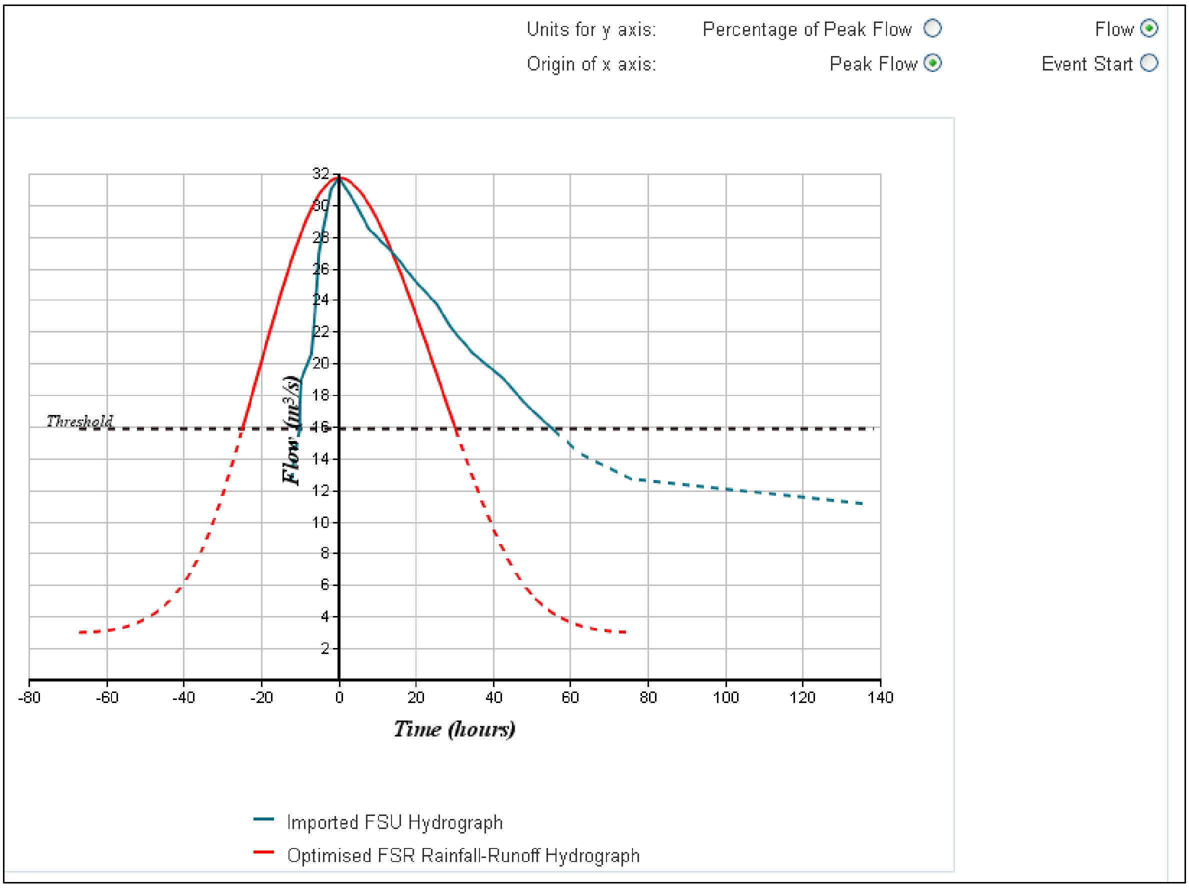
Threshold flow is less than 2 [etc.] **yr input hydrograph start/end values, please adjust**

IBIDEM fits the FSR hydrograph to the FSU hydrograph for flows above a threshold value. By default this is set to 50% of the peak. If the imported FSU hydrograph starts or end at a flow which is higher than this threshold, the fitting will not work. The user needs to either raise the threshold or extend the imported hydrograph so that it starts and ends at a flow below the threshold.

If all the inputs are satisfactory, IBIDEM will move on to the Compare Hydrographs screen, which shows a graph of the fitting and a table of the results.

The graph (shown below) compares the imported and fitted hydrographs. The threshold flow above which the hydrographs were fitted is shown as a horizontal dashed black line. Below the threshold, the hydrographs are shown as dashed lines.

The hydrographs are always plotted with their peak times coinciding. By default, the hydrographs are plotted as percentages of the peak flow, and the origin of the x axis is set to the time of the peaks. These options can be changed using the toggle buttons above the graph.



If hydrographs have been imported for more than one return period, the user can choose which return period will be displayed in the hydrograph plot. Alternatively, the *Variables v Return Period* option displays a graph showing how various variables (peak flow, percentage runoff, SPR, Tp, rainfall depth or runoff volume) change with flood probability The user can select one variable to plot at a time. There are three options for the variable used to display probability. A subsidiary axis indicates the corresponding return period (on the annual maximum scale).

Below the graph is a results table. It shows the fitted values of time to peak (Tp) and standard percentage runoff (SPR) and the resulting values for other variables used in the rainfall-runoff method. If hydrographs have been imported for more than one return period, the table shows a column for each return period. The row showing baseflow (BF) is shaded grey to indicate that baseflow does not vary with return period.

Flow Units: m^3/s ◉ mm/hr ○

Volume Units: m^3 ○ cumec-hr ○ mm equivalent of catchment runoff ◉

Flow Return Period (yrs)	100
Rainfall Return Period (yrs)	140
BF (m^3/s)	2.99
Tp (hr)	31.11
SPR	35.5
PR	45.5
Timestep (hr)	1.00
Duration (hr)	65.00
Rainfall Depth (mm)	124.6
Peak Flow (m^3/s)	31.71
Volume (mm equivalent of catchment runoff)	73.31
RMSE (hr)	6.00
Nash-Sutcliffe Efficiency	-0.569

Export

The options above the table allow the user to change the units for flow or volume. Flow can be expressed as either m^3/s or mm/hr of runoff across the catchment. Volume can be expressed as either mm equivalent of catchment runoff (default) or m^3 or cumec-hours. The latter unit should be interpreted similarly to a person-day, i.e. it represents $1m^3/s$ sustained for one hour, or $3600m^3$.

The last two values in the results table are measures of how well the fitted hydrograph matches the input one. They are calculated in quite different ways:

- RMSE is calculated as part of the fitting. It is the root mean square error in terms of hydrograph width (measured in hours) for the upper portion of the hydrograph over which the fitting was carried out It indicates how well the hydrographs match in terms of width. The RMSE value output by IBIDEM should always be the minimum possible value given the shape of the input hydrograph and the family of possible shapes that the FSR rainfall-runoff hydrograph can take.
- The Nash-Sutcliffe efficiency, which is dimensionless, is calculated in the vertical (flow) direction. It is a measure of the goodness of fit in terms of flow over the entire duration of the imported FSU hydrograph. Values closer to 1 indicate a better fit. Negative values indicate that a better fit could be achieved using the mean flow. This statistic is calculated independently of the fitting done by IBIDEM, and so it will usually not take the minimum possible value.

Error messages

IBIDEM will give an error if the fitted values of Tp or SPR, or the resulting value of PR (percentage runoff) are outside physically feasible limits. A message similar to this will appear at the top of the screen:

ERROR- Inferred SPR value is invalid (more than 100%)

This could happen when the peak of the input hydrograph is unrealistically high or low given the nature and size of the catchment. The user should check the peak flow of the input hydrographs and/or the catchment descriptors that have been supplied to IBIDEM.

Options

Below the output table are three tick boxes that allow the user to assess sensitivity of the FSR design hydrograph to various aspects of the rainfall-runoff method. No further optimisation is carried out within these options; instead the FSR rainfall-runoff method is re-run with the appropriate parameter changed. The options are:

- **Sensitivity to storm duration**

  The FSR rainfall-runoff method is re-run with a variety of different storm durations (five in all). Default values are. 0.5D, √0.5D, D, √2D and 2D where D is the duration resulting from the Tp value found in the optimisation. The user can change the durations if desired.

  This option may allow IBIDEM to provide a useful route to generating realistic hydrograph shapes for inputs to river models, for example in situations where a more prolonged hydrograph is required as an input in order to generate a T-year flood further down the river system.

  The results are shown either as a graph showing multiple hydrographs (one for each duration, plus the input FSU hydrograph) or a graph showing how variables (peak flow, percentage runoff, rainfall depth or runoff volume) change with storm duration. The user can select one variable to plot at a time. This provides a straightforward way to identify the critical duration for a catchment, by plotting peak flow against duration.

- **Sensitivity to changes in urbanisation**

  IBIDEM calculates revised values for Tp and PR to reflect the change to URBEXT. The output is shown on a graph comparing the imported FSU hydrograph, the original fitted FSR hydrograph and the altered FSR hydrograph resulting from the changed urbanisation.

- **Sensitivity to changes in model parameters**

  If Tp is altered, storm duration is automatically updated. If SPR is altered, PR is updated. Other settings remain unchanged. The option allows users to investigate possible impacts of land use change, by adjusting Tp or SPR to represent "before" and "after" catchment conditions, where the user trusts the FSR rainfall-runoff method to represent a particular land-use change (such as agricultural drainage or tree planting). The output is shown on a graph similar to that for the urbanisation option described above.

Outputs

The [Export] button below the table of results allows the user to export a .CSV file containing the input and fitted hydrographs and a summary of the variables. All the graphs produced in IBIDEM can be exported by right-clicking and selecting Save Picture As… or Copy.

Appendix: Error and warning messages

Message	Explanation
Error messages	
2 yr input hydrograph value(s) are less than *xx* m^3/s baseflow value, please adjust	The imported hydrograph includes flow values that are less than the baseflow, which (by default) is calculated by IBIDEM using the FSR procedures. The user needs to either import a hydrograph with a higher minimum flow (e.g. removing the first or last few time steps in the hydrograph) or reduce the baseflow. The calculated value of baseflow can be overridden.
Threshold flow is less than *x* yr input hydrograph start/end values, please adjust	IBIDEM fits the FSR hydrograph to the FSU hydrograph for flows above a threshold value. By default this is set to 50% of the peak. If the imported FSU hydrograph starts or end at a flow which is higher than this threshold, the fitting will not work. The user needs to either raise the threshold or extend the imported hydrograph so that it starts and ends at a flow below the threshold.
ERROR- Inferred SPR value is invalid (more than 100%)	This could happen when the peak of the input hydrograph is unrealistically high given the nature and size of the catchment.
ERROR – Inferred PR value is invalid (more than 100%)	This would typically happen if SPR>100.
ERROR- Inferred SPR value is invalid (non-positive)	This could happen, for example, when the peak of the input hydrograph is unrealistically low and the catchment is urbanised. After the urban component of the PR is calculated by IBIDEM, it can be necessary to use a negative SPR in order to match the input peak flow. The most likely cause will be that the FSU peak flow is too low, for example due to failure to incorporate an adequate urban adjustment in QMED. Alternatively, the catchment may not be well represented by the structure of the FSR rainfall-runoff model or the composition of the design event used as the input to the model.
Warning messages	
WARNING - Inferred SPR is unusually low	This occurs when the fitted SPR is between 0 and 10%. These low values may be valid if the catchment is highly permeable. But it could otherwise be caused by the problems mentioned above, e.g. an unrealistically low input peak flow.
WARNING - Inferred SPR is unusually high	This occurs when the fitted SPR is between 60 and 100%. This may be valid if the catchment is extremely impermeable. But it could otherwise be caused by an unrealistically high input peak flow.
WARNING – Inferred PR is unusually high	This occurs when the fitted PR is between 75 and 100%. This warning is likely to accompany the one above about an unusually high SPR.