AUTOMATED FLOOD ESTIMATION USING GIS

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ABSTRACT

There is an increasing demand for regional or national-scale provision of flood estimates, for example in catchment management or climate change impact studies. This paper describes how a GIS-based system was developed for estimating design flows along 18,000 km of watercourses throughout Ireland.

For such a large scale study it is essential to apply an automatic method. The challenge in developing such a method is to incorporate local information (such as flow data) and account for some of the particular hydrological features of Ireland, such as extensive peatlands and loughs, and arterial drainage schemes. Because the Flood Studies Report methods are not readily automated, the system was based on Flood Estimation Handbook (FEH) methods. The FEH was originally developed for the UK, and several of its concepts are being applied in the ongoing Flood Studies Update research for Ireland. In applying FEH methods to Ireland it was necessary to derive catchment descriptors by combining a digital terrain model with thematic datasets such as soils and climate.

The paper explains how GIS was used to create catchment descriptors and derive design flows at 200m intervals along watercourses, incorporating flood peak data both from local gauging stations within the catchment and from more distant but hydrologically similar stations within Ireland and the UK.

1. INTRODUCTION

Requirement for large-scale flood estimates

The recent period of economic growth is leading to mounting pressure for development on land that is increasingly at risk from flooding. The escalating social and economic impact from flooding has been seen in recent events, such as in January 2000 along the River Shannon, in the South and East in November 2000, along the East Coast following exceptional sea levels in February 2002, in Dublin and other areas in November 2002 and in many parts of the country in October 2004.

The Government's strategy for flood management calls for considerable emphasis on non-structural flood management measures, for example, flood warning systems, flood mapping, guidelines on development and formulation of catchment flood risk management plans to foster a catchment-based approach to flood management (Adamson, 2003).

All such measures need to be based on consistent hydrological information, including flood flow estimates for various return periods at numerous locations throughout a river system. There is also a demand for such information by studies examining the impacts of climate change on flood risk.

The system described in this paper was developed in 2005 to meet the needs of a floodplain mapping study which covered approximately a quarter of Ireland's land area, including all the major urban areas. Since this amounted to 18,000km of watercourses, manually deriving design flows was out of the question.

Reasons for choosing the FEH approach

Current practice is to base flood estimates on the Flood Studies Report (FSR). However, the FSR involves manual derivation of catchment characteristics from maps, which is not readily automated. It is also rather dated, and will shortly be superseded by the current Flood Studies Update (FSU) research (OPW, 2007).

To obtain good estimates of design flows within the time available for the study, the methods described in the UK Flood Estimation Handbook (Institute of Hydrology, 1999) were applied to Ireland. The Flood Estimation Handbook (FEH) has superseded the FSR in the UK, and many of its concepts are being applied in the FSU research. Although the FEH methods were developed using only UK data, when applied they can incorporate a large amount of information from local flow data. It is therefore possible, in principle, to apply FEH methods in areas outside the UK that are sufficiently similar in terms of climate and other hydrological characteristics. Many parts of the Republic of Ireland are geographically similar to Northern Ireland and the wetter and less permeable areas of mainland Britain. There are some particular features of the hydrology of Ireland which warrant special attention, and these are discussed towards the end of this paper. Application of the existing FEH procedures to Ireland was not expected to give results as good as could be obtained from a complete revision of Irish methods, as is currently underway. However, it was anticipated that it might be possible to attain in the order of 80% of the accuracy of a complete revision with around 20% of the effort and time required.

The FEH consists of a set of procedures and data from which design flows can be estimated for any river catchment in the UK (with a minimum catchment size of $0.5km^2$). A design flow is a flow of a specified probability, which in the FEH is expressed as a return period, i.e. the 100-year flow is that which can be expected to be exceeded on average once in 100 years.

Results can be obtained both for sites where flow data is available (*gauged catchments*) and other locations (*ungauged catchments*). For ungauged catchments, flood estimates are made from catchment descriptors, i.e. physical properties of catchments such as area, rainfall and soil type. However, it is often possible to improve such estimates using flow data from nearby or similar catchments. FEH methods use nine different catchment descriptors.

There are two principal FEH methods, the statistical method and the rainfall-runoff method. Both can be used to estimate peak flows, but the rainfall-runoff method also provides a hydrograph shape. The statistical method is generally preferred in many cases, so it is also possible to adopt a hybrid technique, for example one in which the hydrograph from the rainfall-runoff method is scaled by the peak flow from the statistical method. The FEH was originally intended for manual application, but the statistical method has also been automated (Morris, 2003) to produce design flows for all watercourses in Great Britain.

The statistical method uses flow peak data to estimate the *index flood*, QMED (defined as the median annual maximum flow) and to estimate flood *growth curves*, from which design flows for any return period can be obtained. The index flood can be estimated from data at or near the site of interest, or using flow data from more distant but hydrologically similar catchments. Flood growth curves are estimated from a *pooling group*, a group of gauged catchments judged hydrologically similar to the catchment of interest.

2. METHODS

Outline of study

The study involved three main elements:

1. Creating a database of flood peaks and classifying each gauging station according to the quality of high flow data.
2. Creating digital catchment descriptors from available geographical data covering Ireland.
3. Development of an automated method for calculating design flows. This is a simplified version of the procedure used to automated the FEH statistical method for Great Britain.

The result is a GIS-based system that can be used to calculate design flows at most locations in Ireland.

Flood peak database

FEH methods principally use annual maximum flows. These were obtained for 124 flow gauging stations that were initially thought to be of adequate quality, most stations being those operated by the Office of Public Works. The mean record length was 36 years.

The quality of peak flow data tends to be very variable, because many rating curves are derived mainly for measuring low to medium flows, rather than flood peaks. The quality of gauging stations was classified in the same way as the Hiflows-UK project (Spencer *et al.*, 2004), according to their suitability for deriving the index flood and for pooling. Using information obtained from the gauging authorities, 111 stations were judged to be suitable for deriving the index flood and 103 for pooling. 93% of those judged suitable for the index flood have subsequently been classed similarly by the FSU (i.e. categories A or B). These numbers of stations can be compared with the 108 being used in the FSU flood frequency analysis research.

All flood peak series were manually assessed for quality problems. Some gauging stations showed large changes in the magnitude of peaks as a result of arterial drainage schemes. In these cases, the analysis was limited to the post-drainage scheme data.

Flood peak data classed as suitable for pooling was combined with the Hiflows-UK dataset to create a single dataset for UK and Ireland from which pooling groups could be created.

Creating catchment descriptors

Catchment descriptors represent the physical characteristics of catchments. They are used by FEH methods to estimate design flows at locations without flow data, to identify hydrologically similar catchments and to calculate model parameters. The FEH statistical method requires the following catchment descriptors, which are obtained by combining a catchment boundary (derived from a hydrological digital terrain model) with geographic data:

- Catchment area (AREA)
- Standard period annual average rainfall (SAAR)
- Urban extent (URBEXT)
- Index of flood attenuation due to reservoirs and lakes (FARL)
- Standard percentage runoff from HOST, which is a hydrological classification of soil types (SPRHOST)
- Baseflow index from HOST (BFIHOST)

Additionally, the rainfall-runoff method needs the following:

- Mean drainage path length (DPLBAR)
- Mean drainage path slope (DPSBAR)
- Proportion of time the catchment is saturated (PROPWET)

Many of the above catchment descriptors are being used in the FSU research (OPW, 2007). The above set of catchment descriptors was used to apply FEH methods to Ireland. Ireland is not covered by most of the geographic data used to derive the original FEH catchment descriptors for the UK. In some cases, equivalent datasets could be identified. Rather more effort was needed to derive some other datasets, making the best use of available digital information and accepting that it would not be possible to obtain data of the same quality as the original FEH in the time available. In brief, the following information was used:

- A digital elevation model (DTM) with 20m grid size, processed to be “hydrologically correct”, i.e. to ensure that drainage paths can be followed continuously from source to sea. A digital river network was used to aid the processing. The DTM was used to obtain catchment boundaries and land form descriptors.
- A vector map of lake shorelines which was connected to the river network and used to derive FARL.
- A grid of annual average rainfall for 1961-90, used for SAAR and also to assist in an approximate calculation of PROPWET.
- Land cover data from the CORINE Land Cover 2000 project (Bossard *et al*, 2000), used to identify urban areas and to assist in developing the HOST classification for peatlands.
- The General Soil Map of Ireland, which shows 44 soil associations (Gardiner & Ratford, 1980). This was used, in conjunction with a partial map of Quaternary deposits (subsoil) (Fealy *et al.*, 2004) and the CORINE data, to derive a provisional HOST classification for Ireland.

All digital datasets were manually checked and adjusted, for example to add recent urban developments to the CORINE data and to ensure that lakes were properly connected to the drainage network.

The largest amount of effort went into the HOST classification. The 29 HOST classes were developed for the UK and are based on features such as the flow mechanisms and permeability of the soil substrate, the depth to an impermeable or gleyed layer, and the presence of absence of peat (Boorman *et al.*, 1995). The requirement for this project was not to produce a full HOST classification for Ireland, but rather to obtain enough information to produce good estimates of the hydrological variables SPRHOST and BFIHOST.

An initial map was produced by expert judgement, identifying equivalent HOST classes for each soil association on the General Soil map. Some associations (those containing a significant proportion of gleys, which tend to occur in valley bottoms) were allocated a mixture of two HOST classes. Next, additional spatial detail was added by subdividing some associations into several HOST classes using information on the depth of groundwater interpreted from the Quaternary mapping. The classification was also refined, particularly in peat areas, using the CORINE data (which identifies features such as inland marshes, raised bogs and improved pasture). Figure 1 shows the resulting map of SPRHOST (standard percentage runoff).

The provisional HOST classification was checked against other sources of information, including the HOST map for Northern Ireland and border areas of the Republic of Ireland (Higgins, 1997)), the Flood Studies Report map of Winter Rainfall Acceptance Potential and a map of overland runoff risk (Gleeson, 1996). Advice from current and retired staff of Teagasc (the Agriculture and Food Development Authority) proved helpful in developing the classification. There is clearly potential for improvements, in particular incorporating information from the more detailed county soil maps. However, these had not been completed at the time of the project.

Catchment descriptors were evaluated at 200m intervals along drainage paths using a specially developed suite of GIS tools in ArcGIS.

Automated calculation of design flows

FEH methods allow considerable scope for incorporating user judgement and local knowledge. Some of this is clearly not feasible when the methods are applied automatically to numerous locations. However, when CEH Wallingford automated the statistical method for Great Britain (Morris, 2003), they devised rules that mimic the decisions made by hydrologists. The main challenge in automation was to adhere to FEH rules and guidance as far as possible while avoiding or reducing spatial inconsistencies, i.e. sudden unjustified changes in design flows between adjacent locations.

Most of the modifications introduced by CEH Wallingford concerned the adjustment of QMED values estimated from catchment descriptors. The FEH recommends seeking either a donor site (a gauged catchment, usually on the same watercourse as the subject site) or an analogue site (a more distant but hydrologically similar gauged catchment). At the donor or analogue site, a QMED adjustment factor can be obtained by comparing QMED estimated from catchment descriptors with that derived from flow data. This ratio is then used to adjust QMED at the subject site. Often there will be more than one suitable donor or analogue site. CEH developed complex procedures to identify donors and analogues, moderate their influence and calculate weights where there is more than one donor/analogue. The way that pooled growth curves are calculated was also altered.

A revised automated scheme was developed for application to Ireland. It was intended to reduce the complexity of the CEH scheme; address concerns over the arbitrary nature of some aspects; and suit some of the particular features of Ireland. However, many aspects of the CEH scheme were found to work excellently and were retained. A full description of the technique is not possible in the space available, but essentially the scheme for adjusting QMED values was designed to:

1. Match estimates of QMED from flow data at each gauging station judged suitable for QMED, to ensure consistency with any detailed local studies that will almost always base QMED at gauging stations solely on flow data.

2. Smoothly vary QMED for locations along a watercourse between two gauging stations that act as donor sites. Two was the maximum number of donors allowed.

3. Moderate the effect of a single donor so that its influence gradually declines to nil at a point where the catchment is sufficiently different from that at the gauging station.

4. Seek analogue sites at locations where there are no suitable donors. Gauging stations throughout Ireland (North and South) were considered as potential analogues. Stations from Great Britain were not used because errors in the QMED equation tend to be spatially clustered (both in Great Britain and Ireland), so local analogues are preferable. Up to five analogues were allowed, with priority given to local catchments. More similar analogue sites are given more weight in the adjustment of QMED.

An important aspect of the scheme was to define what is meant by "hydrologically similar". This was done using similar limits on catchment descriptors to those proposed by CEH, for example allowing analogue stations with an area up to four times larger or smaller than that draining to the subject site.

Figure 2 shows an example of the resulting QMED adjustment factors in the catchment of the River Blackwater upstream of Mallow, County Cork.

At each location where a flood estimate was needed, a pooling group was selected. Gauging stations throughout the UK and Ireland were included in pooling groups, because the similarity of flood growth curves depends more on the physical properties of catchments than on their location, which is why the FEH moved away from the concept of growth curves for geographic regions. Inclusion of UK data also allowed pooling groups to incorporate some of the longer flood peak records available in Great Britain. The FEH recommends that the number of stations in a group should be increased until there are 5T years of data, where T is the principal return period of interest (100 years in this case).

The pooled growth curve was derived by averaging flood frequency statistics (represented by L-moments) over the pooling group. As in CEH's automated method, the FEH similarity ranking factor for calculating pooled L-moments was replaced with a similarity weighting factor SWF, based solely on similarity of the station to the subject site in terms of catchment descriptors. A Generalised Logistic distribution was fitted for each location and adjusted for urbanisation using the standard FEH procedure. Finally, design flows were obtained by multiplying the growth factors by the estimated value of QMED.

A hydrograph shape was fitted to each peak flow using the procedure described as "Borrowing a standard hydrograph shape from the rainfall-runoff method" in Volume 3 of the FEH.

The automatic method described above was implemented in ArcGIS by developing procedures for searching through the watercourse network to automatically identify potential upstream and downstream donor sites and set adjustment factors for QMED, and then running through the rest of the calculations to arrive at a set of design flows.

3. PARTICULAR HYDROLOGICAL FEATURES OF IRELAND

Some features of Irish catchments are rare or absent in the UK and so require special consideration when applying a method originally developed for the UK. These include:

1. Peatland areas

Central counties contain extensive lowland raised bogs that have developed in former lake basins. In terms of flood hydrology, despite to the popular idea of peatlands behaving as "sponges", bogs tend to act as areas of high runoff although this effect can be counteracted by artificial drainage which lowers the water table and hence increases the storage capacity (Wilcock, 1979). For example, Ingram (1987) found that Scottish mires hold a great deal of water in permanent storage but the capacity of temporary storage (e.g. of storm water) was very low. Catchments with extensive mires would therefore be expected to generate high and rapid runoff peaks.

Bogs once covered 16% of Ireland, but 82% have been altered or lost due to drainage or peat extraction (IPCC, 2002). The runoff characteristics of areas where peat has been removed depend on the degree of peat removal and the method of restoration. For cutover (mechanically extracted) peat, much of the storage capacity is lost and so in general percentage runoff can be high, despite the drainage that typically accompanies peat extraction.

The effects of peatlands have mainly been accounted for by the HOST mapping. The presence of a peaty surface layer is one of the four main characteristics of the HOST classification. Undrained peat soils are allocated a high value of standard percentage runoff (60%). As for the other features discussed here, the use of local flow data also helps to account for the effects of peatlands on many watercourses.

2. River arterial drainage schemes.

Many watercourses have been subjected to large-scale deepening and widening, usually aimed at improving agricultural drainage.

A recent summary research on the impacts of arterial drainage on flood behaviour is given by Bhattarai and O'Connor (2004). Most studies have shown that the immediate effect of arterial drainage is to increase peak flows. However, the effect appears to decline with time (presumably due to geomorphological re-adjustment by the river). Drainage also tends to increase the speed of flooding. An earlier study by Bailey and Bree (1981) showed that drainage schemes increase design flows by an amount that does not vary with return period, equal to 60% of the 3-year return period flow. Catchments with a significant lake influence showed much smaller changes. The results of this study were adopted as design guidance by the OPW (1981).

Where flow data are available on catchments that have been subject to drainage schemes, only post-scheme data have been used for deriving QMED. On ungauged watercourses, the effects of drainage schemes are harder to represent. When similarly drained watercourses are used as donors or analogues, an improvement in the QMED estimate can be expected (but not guaranteed). There is potential for further research here, for example developing a catchment descriptor that measures the degree of drainage works.

Flood growth curves have not been adjusted to account for drainage schemes, following the finding of Bailey and Bree (1981) that the gradient of the flood frequency curve is unchanged.

It is also necessary to consider the influence of drainage on the hydrograph shape. Bailey and Bree found that on seven drained catchments without lakes the time to peak was well predicted from catchment descriptors by the Flood Studies Report equation. It can be expected that the newer FEH equation will perform similarly well. Presumably drainage of Irish catchments was making them behave more like average British catchments.

3. *Unusual karst features such as turloughs.*

40% of Ireland is underlain by limestones, many of which are karstified (Karst Working Group, undated). In many areas the limestones are covered by glacial till, but where there is no impermeable drift cover, karst features can transmit large volumes of water in conduits and store water in turloughs, which are temporary lakes. When turlough storage capacity is exceeded, widespread and prolonged flooding can result. Both river flood statistics and floodplain extents on strongly karstic catchments are unlikely to be well predicted from catchment descriptors. In the absence of local flow data, karst effects are unlikely to be well accounted for without detailed studies such as that carried out in the 1990s in the Gort-Ardrahan area of South Galway (Lees *et al.*, 1998). Such detailed modelling was outside the scope of the present study.

The permeable catchment adjustment in the FEH statistical method (Faulkner & Robson, 1999) was applied to ensure that any unusually low annual maximum flows, sometimes recorded on permeable catchments, did not introduce a bias into the flood estimates.

4. *Extensive lough systems.*

There are many large loughs in the west, particularly in the Shannon catchment, that strongly attenuate flows. Outflows from some loughs are controlled as part of hydro-electric schemes (Fitzpatrick & Bree, 2001), although control is often limited in flood conditions (Cullen, 2002).

The methods allow for the effects of loughs in three ways. First, the value of QMED is reduced on catchments where the FARL value is less than 1, indicating that flood peaks are likely to be attenuated by lakes or reservoirs. The QMED equation was calibrated using UK gauged catchments, within which the lowest FARL value was 0.67. The lowest FARL value at an Irish gauging station was found to be similar, 0.66 downstream of Lough Corrib at Galway; however lower values occur at ungauged locations. The QMED equation was therefore applied outside of its calibrated range in some cases. However, use of donor and analogue sites enabled incorporation of local flow data.

Flood growth curves may also be affected by the presence of loughs, the main effect being a flattening of the growth curve. This was accounted for by adjusting the pooling group, reducing the weight of gauging stations with FARL values different from that at the subject site. This refinement, introduced in the CEH project, helps to ensure that growth curves for sites with significant lakes in their catchment are derived mainly from catchments with a similar degree of attenuation.

Finally, the duration of the flood hydrograph was extended to represent the change in shape of the hydrograph. This helped ensure that the volume of flood water was not reduced as a result of lowering the peak flow.

4. RESULTS

It is difficult to validate design flood estimates for long return periods without the benefit of very long flood peak records. However, some elements of the results can be validated, and others have been checked against previous studies.

One of the assumptions made for the study was that the FEH equation for estimating the index flood, QMED, from catchment descriptors would perform reasonably well in Ireland. This was tested by applying the equation at the sites of gauging stations and then comparing the resulting estimate with QMED calculated directly from the annual maximum flow data. Figure 3 shows that there is a good correlation (compare with Figure 13.7 in Volume 3 of the FEH). The factorial standard error is 1.703, which compares well with 1.549 which was obtained when the QMED equation was applied on the UK data from which it was originally calibrated.

The pooled flood growth curves, which are used to generate design flows for return periods longer than 2 years, have been compared with results from previous studies. At the sites of gauging stations, the pooled 100-year growth factor (i.e. 100-year flow divided by QMED) was found to vary from 1.58 to 3.18. The mean value was 2.07 and the median 2.00. These are very close to the equivalent value derived from the Flood Studies Report growth curve for Ireland, 2.06. The FSR curve was derived from stations with only 15 years of data on average. Recently, Cawley & Cunnane (2003) proposed an updated flood growth curve for Ireland, with a 100-year growth factor (when standardised by QMED) of 1.92. They found that growth rates were generally higher in the east and lower in the wetter west. While the similarity of all these figures is encouraging, the variability of the growth curves derived in the present study suggests that more accurate flood estimates can be obtained by moving away from the concept of a fixed regional growth curve.

5. CONCLUSIONS

1. This was the first attempt to produce flood estimates on such a scale in Ireland and also the first widespread application of Flood Estimation Handbook-style techniques in Ireland.

2. FEH techniques offer several advantages over the Flood Studies Report (the current standard estimation method for Ireland), including:

    a. Deriving catchment descriptors from digital data, rather than paper maps, which allows automation, consistency and the use of more sophisticated descriptors. The new catchment descriptors also incorporate more up-to-date information, for example on soil types and urbanisation.

    b. Pooling groups, which are created individually for each site of interest and are more likely to be statistically homogenous than the fixed geographic regions used in the Flood Studies Report.

    c. More up-to-date methods of statistical flood frequency analysis, such as the use of L-moments to fit flood growth curves.

    d. Greater scope for incorporating local flood peak data, rather than relying solely on equations that are inevitably calibrated for average conditions.

3. Results of this study were found to compare well with measured flow data (in terms of QMED estimates) and to closely match previous studies (in terms of flood growth curves).

4. The Flood Studies Update project will provide a more comprehensive methodology, including for example a QMED equation calibrated specifically for Ireland. Flow data have been more rigorously quality controlled for FSU, and improved catchment descriptors are being developed. However, the study described in this paper demonstrated what can be achieved with readily-available data in the short time of 9 months. It also points to the future potential of automating the methods developed by FSU.

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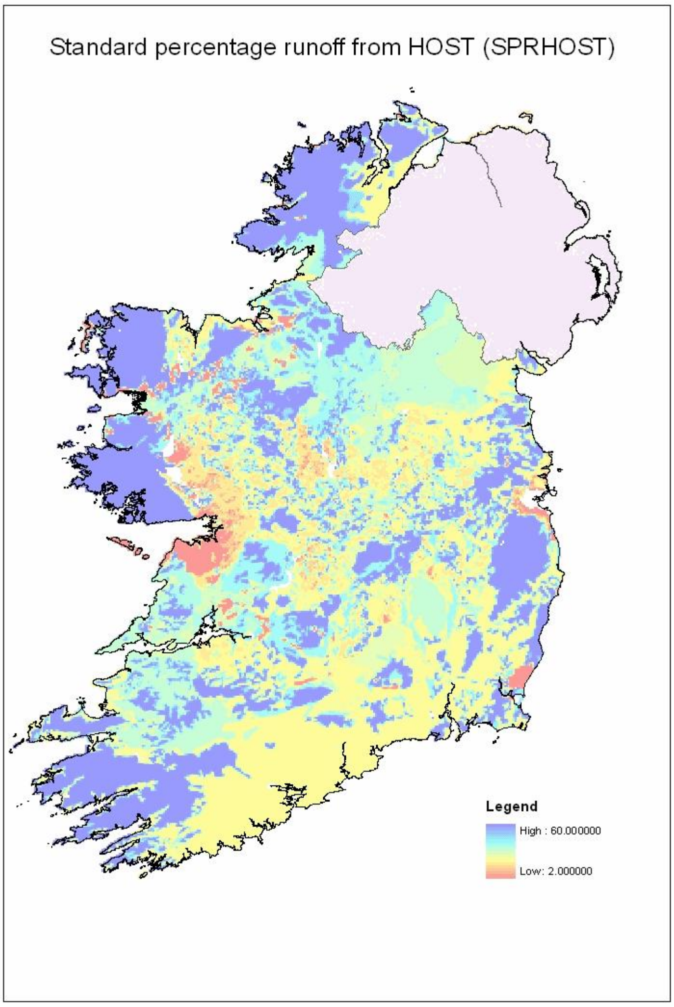

Figure 1: Map of standard percentage runoff from HOST (SPRHOST)

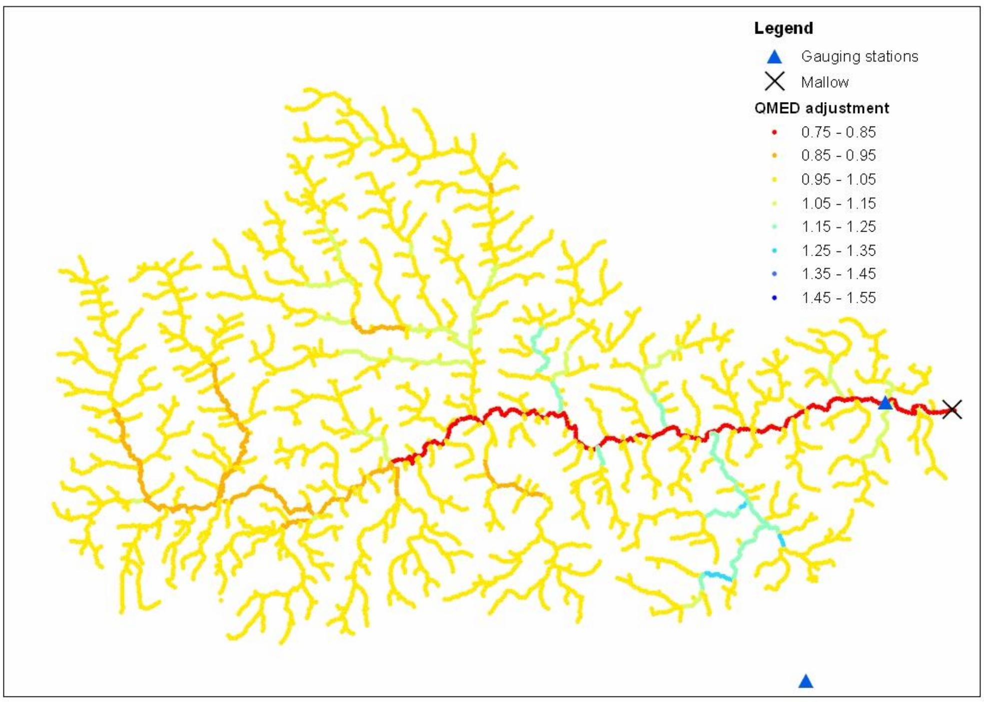

Figure 2: Map of QMED adjustment factors in the Blackwater catchment, County Cork

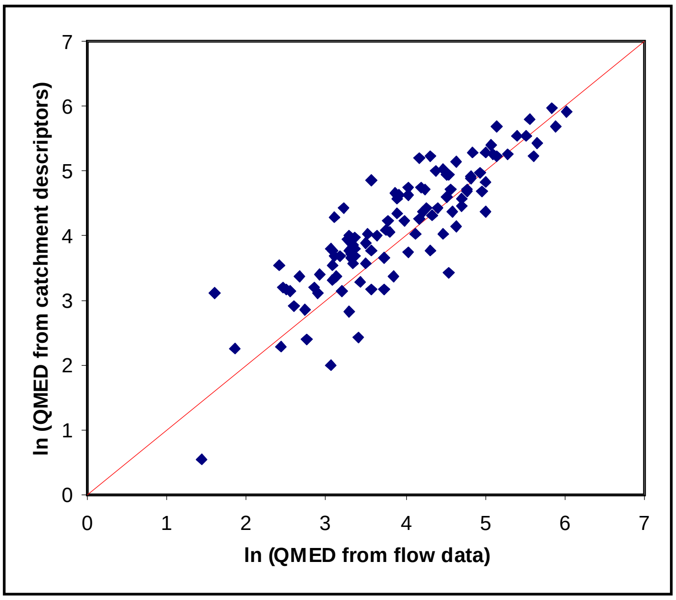

Figure 3: Comparison of observed and predicted QMED values