

*Environmental Protection Agency
and Wallingford HydroSolutions Ltd*

Flow Duration Curves for Ungauged Catchments in Ireland

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*Annual and Monthly
Flow Duration Curves and Mean Flows*

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1 Introduction and Summary

The Environmental Protection Agency (EPA) in Ireland has commissioned an update to a hydrological model for estimation of annual flow duration curves (FDCs). These curves plot river flow against percentage of time flow is exceeded and they are used in assessment of natural flows, environmental flows and abstractions. Launched in 2009, the original model was embedded within a web-based system consisting of a database, a series of mapping tools and reporting procedures. This system has been updated and extended by EPA and Wallingford Hydrosolutions (WHS) Ltd using WHS's "Qube" system and the updated model is applied within the new system.

The development of the original model is described initially in this report and the statistical procedures in the updated model are presented, with a re-analysis of additional and updated data. The model generates natural flow duration curves in ungauged catchments from flows at gauged catchments of similar character, using a procedure called Region of Influence which is based on catchment descriptors. The annual FDC procedures are extended to estimate annual mean flows, monthly flow duration curves and monthly mean flows.

All comparisons between catchment flows are made in flow per sq km. It was found that the most significant descriptors to be used in the choice of similar gauged catchments are SAAR, standard average annual rainfall, and PDP, the total area with poorly drained and peat soils. The final model uses these two descriptors at all percentiles of the FDC, together with one other: RkcRK, karst area, for high flows; FARL, an index for lakes, for mid flows and PEAT, peat soils, for low flows. The FDC at a target site is estimated using the five catchments that are closest to the target catchment in terms of these descriptors, by weighting their FDCs with inverse distance in terms of descriptor values; then the weighted average FDC is smoothed.

The estimated FDC Factorial Standard Error (FSE) is shown below where the flow that is exceeded 95% of the time, Q95, has FSE 56%. This is a conservative estimate in most applications. The estimated mean flow, calculated from the estimated FDC, has an FSE of 16%.

Table 1.1 Annual FDC Factorial Standard Error

	Q0.1	Q01	Q05	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90	Q95	Q99	Q99.9
FSE	49%	31%	22%	18%	17%	17%	18%	20%	22%	25%	32%	44%	56%	92%	205%

The possibilities for adjustment with local information should always be considered. The active descriptors in the model are consistent with procedures used in Ireland for estimation of recharge and baseflow.

2 Data Preparation

Flow data in Ireland was assembled and reliability was interpreted, leading to a reasonably independent set of gauged catchments that reflect natural flow conditions across a wide range of topography, soils, subsoils and aquifers. Catchments with digitised flow records were assessed in terms of:

- low flow rating quality
- length of record
- significant abstractions
- regulated reservoirs
- large natural lakes
- local conduit karst pathways and
- correlation with upstream or downstream gauging stations.

2.1 Flow Records

Criteria for reliability of flow data was agreed with hydrometric and environmental authorities.

There were 145 gauging stations in the 2009 model and their locations are shown in Figure 2.1. The colour legend indicates the variation in the 95 percentile flow per sq km (Q95). The range of catchment areas was large, from 2.8 to 2450km² and there was an average of 25 years record. The very dry year 1976 was included at 53% of the sites and there was a wide range of catchment types, in terms of slope, soil, subsoil and aquifers, lakes, etc.

Longer flow records and additional flow gauging sites were added in this update. WHS carried out a detailed review of gaps in the flow records that culminated in more consistent criteria for inclusion or exclusion of each station-year record. For example, there are two gauging stations at Carrickmines, 10003 and 10039, and these were combined into an extended period of record by transferring data.

Some gauging stations were removed as further information on abstractions and catchment descriptors became available.

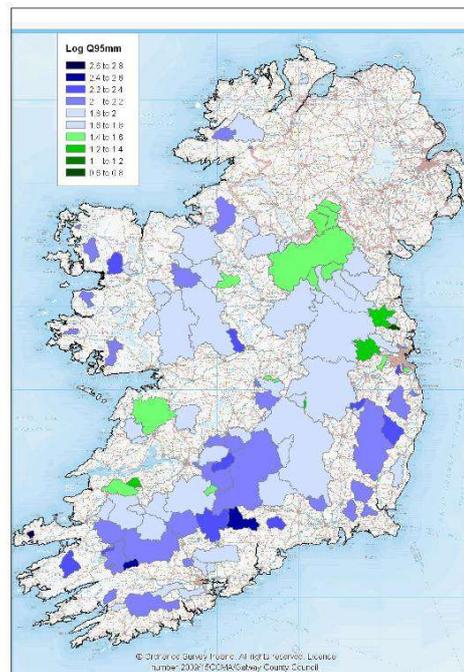


Figure 2.1 2009 Catchments and Low Flows

Outliers were removed during preliminary model fitting. For example:

- Station 25222, Boora at Gorteen Bridge, gave problems at mid to high flows. Located on a tributary draining part of Boora Bog and Lake, it traverses flow pathways on the fringes of an industrial scale peat extraction.
- Station 08012, Stream at Ballyboghill, has a very low standardised Q95 flow.
- Station 22022, Milltown River at Milltown, has the highest low flows per sqkm in the dataset, which appears inconsistent with its high slope, high rainfall and no lakes. It plots as the extreme point on the right of Figure 2.2 below, which shows results of preliminary modelling of Q95.

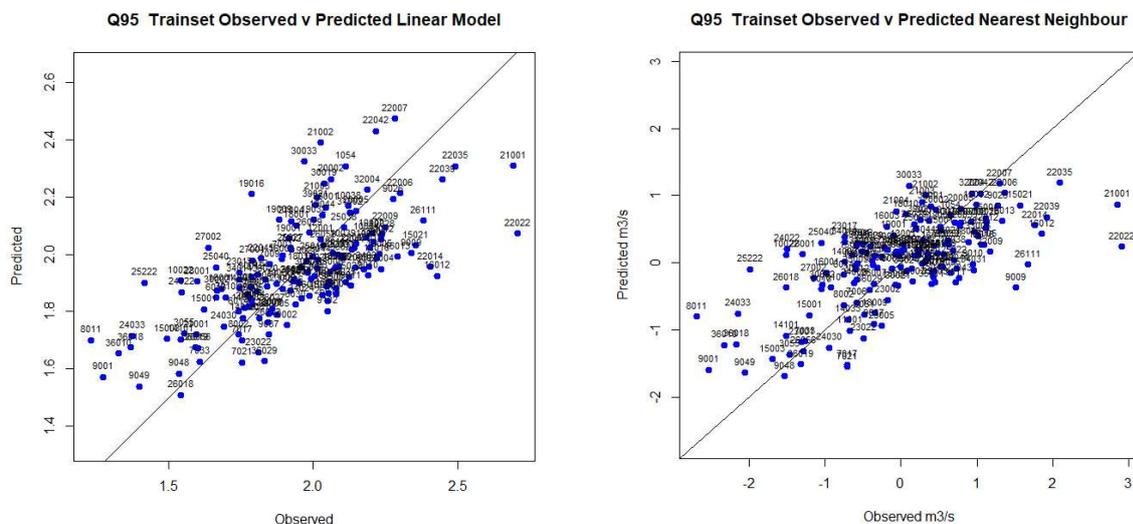


Figure 2.2 Preliminary Linear and Region of Influence Models Observed v Predicted

The data update led to a total of 153 gauging stations as against the original 145 stations in the 2009 dataset. The flow duration curves are shown in Figures 2.3 and 2.4 below, standardised by Catchment Area (AREA). Comparisons were made with standardisation by mean flow and also by AREA x SAAR, i.e. catchment area by standard annual average annual rainfall, a standardisation method applied in a previous FDC study in Ireland in 1985. Neither provided benefits over AREA. Flows were plotted at both natural scale and log scale, against normal probability plotting positions. The log plot exaggerates variations at low flows and diminishes variations at high flows. A straight line on this type of log plot has often been fitted to FDC shapes, equivalent to fitting the Lognormal Distribution.

All flows were analysed in the Log10 domain, where minimising error corresponds to minimising the percentage error in flows per sqkm.

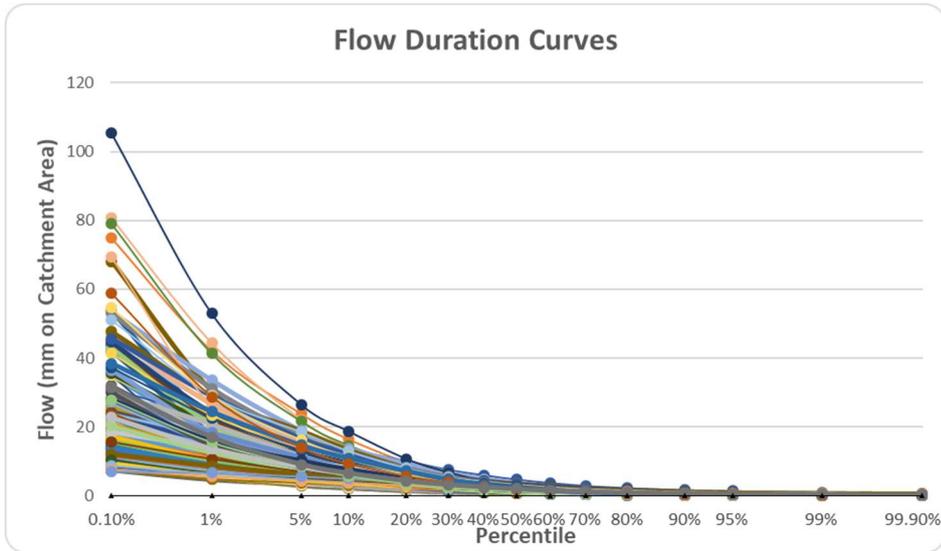


Figure 2.3 *Flow Duration Curves, Natural Scale*

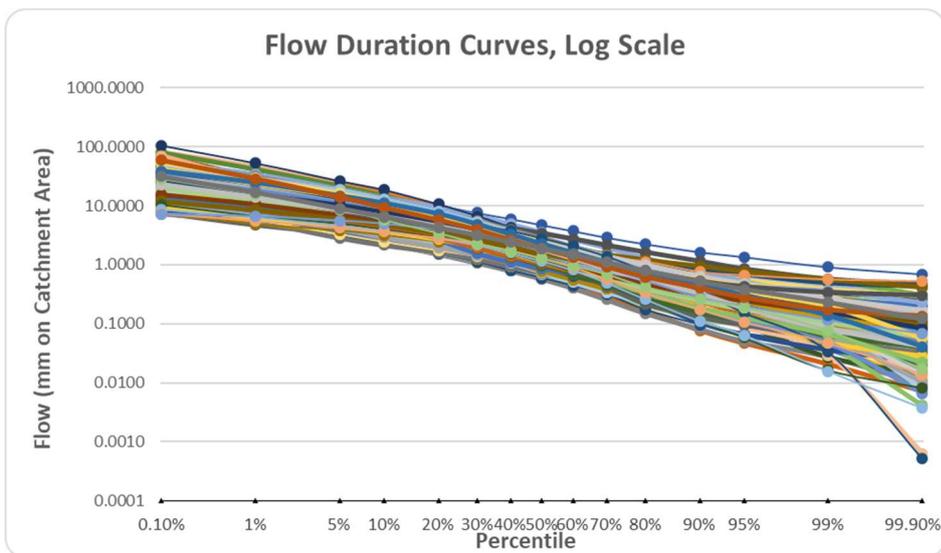


Figure 2.4 *Flow Duration Curves, Log Scale*

2.2 Catchment Descriptors

Catchment descriptors are defined in terms of four groups:

1. Topography and Climate
2. Soil
3. Subsoil Vulnerability / Permeability
4. Aquifer.

In the Topography/Climate group, SAAR for the years 1961 to 1990 is often used as the main climate representation across the country. Total stream length (NETLEN) is stated in kms. Drainage density (DRAINDD) is the number of stream junctions per sq km. Flow attenuation from reservoirs and lakes (FARL) is an index that weights each reservoir/lake area by the catchment area that feeds it. Slope is the average surface topographic slope across the catchment.

There are 27 soil types for Ireland in a mapping system prepared by Teagasc / Irish Forestry Service. There are five subsoil categories and eleven aquifer types, all determined and mapped in groundwater protection plans by Geological Survey of Ireland. An expert group was formed to amalgamate them into a more manageable number of drainage-related categories. The expert group comprised representatives of Teagasc (Agricultural Institute), Geological Survey of Ireland, Environmental Protection Agency and ESB International. The original 27 Soil Types are shown in Figure 2.5, on the left, and the amalgamated six soil drainage descriptors are shown on the right. They are expressed as percentage of the total catchment area, with soil descriptors adding to 100%.

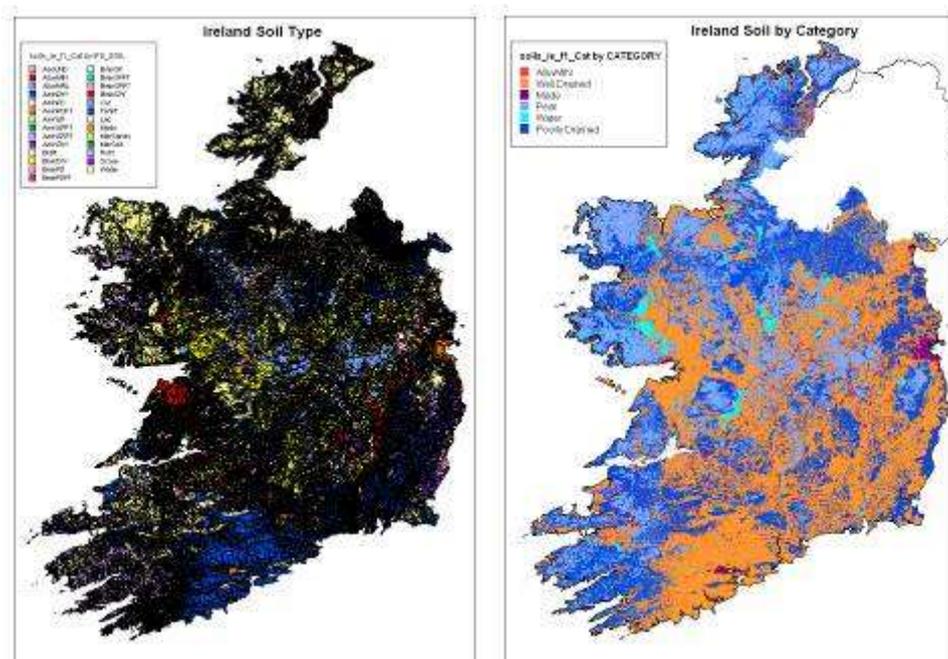


Figure 2.5 27 Soil Types in Original Classification and Simplified Six Soil Categories

The six hydrological soil groups are listed in Table 2.1 below, where the two most prevalent groups are Poorly Drained and Well Drained. The soil type noted as “Made Ground” refers primarily to urban areas and landfill, while “Water” relates to surface coverage by water features such as lakes.

Table 2.1: Soil Drainage Groupings

Soil Drainage Type	No. of Soil Sub-Classes	Hydrological Group
Poorly Drained	13	POORLY_DRAINED
Well Drained	7	WELL_DRAINED
Peat	4	PEAT
Alluvium	1	ALLUV
Made Ground	1	MADE
Water	1	WATER
TOTAL	27	

A national subsoil permeability system has been developed by Geological Survey of Ireland (GSI) for assessment of groundwater vulnerability to pollution. The dataset identifies five subsoil permeability classes, high, moderate, moderate to low and low permeability and unclassified which frequently relates to areas of bare rock, or as yet unmapped subsoils. Areas were mapped in accordance with the definitions in Table 2.2 below and this classification was not reduced.

Table 2.2 Hydrogeological Grouping System of Subsoil

Subsoil Thickness	Hydrogeological Requirements				
	Diffuse recharge			Point Recharge	Unsaturated Zone
	Subsoil permeability and type				
high permeability (sand/gravel)	moderate permeability (sandy subsoil)	low permeability (clayey subsoil, clay, peat)	<i>(swallow holes, losing streams)</i>	<i>(sand & gravel aquifers only)</i>	
0–3 m	Extreme	Extreme	Extreme	Extreme (30 m radius)	Extreme
3–5 m	High	High	High	N/A	High
5–10 m	High	High	Moderate	N/A	High
>10 m	High	Moderate	Low	N/A	High

Notes: (i) N/A = not applicable.
(ii) Permeability classifications relate to the material characteristics as described by BS5930.
(iii) Release point of contaminants is assumed to be 1–2 m below ground surface.

A groundwater bedrock aquifer map of Ireland is also produced by GSI, based on hydrogeological characteristics of the principal rock formations in Ireland published as a separate Rock Unit dataset. In addition, overlying Sand and Gravel aquifers in the country are included in the aquifer dataset. The aquifer data comprises some 11 primary classes. These have been grouped into six groups for catchment hydrological analysis – five bedrock aquifer groups and a single map for overlying presence/absence of sand and gravels aquifer. The original and final set of aquifer categories are shown in Table 2.3 below.

Table 2.3 Six Aquifer Drainage Groups

Aquifer Type	Class Code	Hydrological Grouping
Regionally important karstified aquifer dominated by conduit flow	Rkc	Rkc_Rk
Regionally important karstified aquifer	Rk	
Regionally important karstified aquifer dominated by diffuse flow	Rkd	Rkd_Lk
Locally Important Aquifer – Karstified	Lk	
Locally important aquifer which is generally moderately productive	Lm	Lm_Rf
Regionally important fissured bedrock aquifer	Rf	
Locally Important Aquifer – Bedrock which is Moderately Productive only in Local Zones	LI	LI
Poor Aquifer – Bedrock which is Generally Unproductive	Pu	Pu_Pl
Poor Aquifer – Bedrock which is Generally Unproductive except for Local Zones'	Pl	
Locally important sand/gravel aquifer	Lg	Lg_Rg
Regionally important sand/gravel aquifer	Rg	

The full set of descriptors tested in the FDC model are listed below where the range of values at the gauging stations is also stated.

Table 2.4 Descriptors Considered

Topo/Climate:	AREA sq km	SAAR mm	NETLEN km	DRAIND no/sq km	FARL	SLOPE
Range	1.2 – 2767	725 - 2584	0.8 - 2230	0.5 - 2.71	0.63 - 1.00	1.07 - 32.6
Soils:	PoorlyD	WellD	PEAT	MADE	WATER	ALLUV
Range	1.5 – 84	0 – 97	0 - 88	0 - 63	0 - 10	0 – 10
Subsoils:	EXT	HIGH	MOD	LOW	ML	
Range	0 – 100	0 - 28	0 - 91	0 - 97	0 - 73	
Aquifers:	PuPl	LI	LmRf	RKcRk	RkdLk	LgRg
Range	0 – 100	0 - 100	0 - 79	0 - 100	0 - 76	0 – 76

Excluding AREA, this provided a total of 22 descriptors for the model - six climate/topographic, six soils, five subsoils, five bedrock aquifers and one gravel aquifer.

3 Region of Influence Model

The Region of Influence (ROI) approach allows a wide variation in FDC shapes, as appropriate for a national model. The user's target site is examined and the model chooses from the database system a set of donor gauged catchments for this target site, transferring standardised flow information from the donor catchments.

There are two commonly used approaches when selecting donor catchments:

- The first is the spatial proximity approach, where geographically close catchments are used. This was the most widely used method in hydrology in the past. A FDC study for Ireland was completed in 1985, when the Department of Energy published a report called Small-Scale Hydro-Electric Potential of Ireland. The study was conducted by An Foras Forbartha (precursor organisation to the EPA) and the Electricity Supply Board and it was based on 220 gauging stations. FDCs, standardised with AREA by SAAR, were grouped into geographical regions; an average standardised curve was assumed to apply within each region.
- In the physical similarity or Region of Influence approach, catchments with similar attributes are used as donor catchments. It benefits from availability in recent years of GIS datasets for soils, subsoils and aquifers, in addition to traditional topographical and climatological catchment descriptors as discussed above.

Descriptors were divided by their standard deviations at the gauging stations, so that they are in comparable units before modelling their influence on river flows. Descriptors' unit of measurement is then the number of standard deviations. The standard deviations for the final updated model derived here are shown in Table 3.1 (PDP is the addition of percentage poorly drained soil and percentage peat, to be discussed later).

Table 3.1 Standard deviations at gauging stations

<i>Descriptor</i>	<i>SAAR</i>	<i>FARL</i>	<i>PDP</i>	<i>PEAT</i>	<i>RKcRK</i>
St Deviation	376mm	0.07	27%	21%	21%

The ROI physical similarity model is a type of regression and its application involves the following steps:

1. Identify the catchment boundary of the target site and evaluate descriptors
2. Search the database of gauged catchments' descriptors and associate with each catchment its 'distance' from the target site, in euclidean 'descriptor space'. Descriptor distances may be weighted by descriptor weights.

3. Form a pooling group of donor catchments, comprising the closest “k” gauged catchments to the target, and calculate their average standardised FDCs. Each catchment FDC may be weighted (using separate weights from descriptor weights), depending on its distance in descriptor space from the target catchment. These weights are often called a kernel; equal weights are a uniform kernel, inverse distance weights are an inverse kernel, etc. Note that if all catchments were allowed in the pooling group, and the kernel is uniform, then the result would be a national average standardised FDC, i.e. no model.
4. The final step is to apply the pooling group standardised FDC to the target site.

The model has two sets of weights; descriptor weights and donor weights. Together with k, they form the parameters of the model. Forcing a descriptor weight to be zero eliminates that descriptor. Similarly, once a value for k is chosen, i.e. only the closest k catchments are to be used, then this is the same as forcing all other donor weights to zero based on their descriptor distance.

4 Fitting the Annual Model

4.1 Preliminary Steps

The set of catchments was divided into a calibration (training) set and a validation (test) set, with two thirds of the catchments in the training set and one third in the test set, chosen randomly. All weights and parameters were fitted to the training set by a procedure called “leave-one-out” crossvalidation, minimising the percentage error, i.e. the training Factorial Standard Error (FSE). The trained model was applied to estimate flows at each test site using the closest donors from the training set and finally the test set Factorial Standard Error (FSE) was derived. The complete process was undertaken for each flow percentile which means that the set of donor catchments could vary across the FDC.

To identify significant descriptors, preliminary model runs were made and results compared with a Linear Regression model. The number of descriptors was reduced as follows:

1. Forward and backward elimination was applied.
2. With two descriptors for lakes, denoted FARL and WATER, only one of these was allowed in any model run. High positive and negative correlations within all available descriptors were similarly removed.
3. Five soils descriptors within a catchment are measured as percentage of catchment area. They add to 100% and hence not all were allowed in the model. The same applied within subsoil and bedrock aquifer categories.
4. Principal Component Analysis (PCA) identified descriptors with strong linear relationships among them, as illustrated below in the next section.

Equal descriptor weights and equal donor weights were tested as were varying weights.

The steps above resulted in a reduction in the number of descriptors from the original 22 to eight in the original 2009 model for Q95 and although fewer could suffice for other percentiles, the number eight was maintained across the FDC. A trial and error approach minimised the training error, checking that the FDC was reasonably smooth. Significant descriptors at high to mid flows in the 2009 model were SAAR and NETLEN, and at mid to low flows they were SAAR, SLOPE, FARL and DRAIND. The 2009 set of descriptor weights are shown in Table 4.1.

Table 4.1 Original 2009 Model Descriptor Weights

	5%	10%	50%	90%	95%
SAAR	0.74	0.71	0.59	0.31	0.31
NETLEN	0.52	0.55			
DrainD	0.22	0.23	0.38	0.43	0.43
Farl	0.14	0.07	0.38	0.49	0.49
Slope			0.47	0.52	0.52
PoorlyD			0.07	0.13	0.13
WeilD			0.25	0.28	0.28
MADE			0.10	0.19	0.19
ALLUV	0.11	0.12			
HIGH	0.26	0.28	0.25	0.28	0.28
RkcRk	0.07	0.08			
RkdLk	0.15	0.16			

A pooling group of three catchments was provided in this model. Three systems were tested for averaging the donor catchments' FDCs, i.e. averaging the Log10s:

- simple average, i.e. uniform kernel
- inverse kernel in “descriptor space”
- catchment weights determined by regression across all catchments.

The uniform kernel performed as well as the other methods. The 2009 model test FSE for Q95 was assessed against other methods of estimation, starting from a crude estimation method without any descriptors, moving to the Region of Influence:

<i>Use of National Average of LogQ95:</i>	<i>90 – 100%</i>
<i>Use of AREA and SAAR only:</i>	<i>80 – 90%</i>
<i>Spatial Proximity:</i>	<i>70 – 80%</i>
<i>Region of Influence Weighted Descriptors:</i>	<i>50 – 60%</i>

In all cases, percentage errors for mid-range percentiles were considerably lower, at about 20%.

This model was improved in the present study by applying the updated dataset described in Section 2 above, and by two additional measures during the elimination of descriptors:

1. Extended optimisation and principal component analysis, and
2. Smoothing constraints.

These measures are discussed below. The potential for combining descriptors was considered during the process where appropriate rather than eliminating them. This led to a new descriptor “PDP” which is the total percentage of Poorly Drained and Peat soils in a catchment and another, “MLL”, which is the total percentage of Moderate, Moderate to Low and Low subsoils. Such combinations are extensions to the process described earlier in Section 2.2 when the descriptors were originally prepared.

The annual model was fitted at eleven percentiles: Q0.1, Q01, Q05, Q10, Q20, Q30, Q40, Q50, Q60, Q70, Q80, Q90, Q95, Q99, Q99.9 and also at the mean flow.

4.2 Optimisation and Principal Component Analysis

A programmed Gradient Search method called Hooke Jeeves Algorithm was applied when minimising training error. This used a random search element. It is derivative free and therefore it can deal with step changes when moving from one potential pooling group to another. The search optimisation was implemented using statistical “R” programming and the algorithm was applied together with a crossvalidation routine called “train.kknn”. Documentation references are:

<https://www.rdocumentation.org/packages/pracma/versions/1.7.0/topics/hooke-jeeves>

<https://www.rdocumentation.org/packages/kknn/versions/1.3.1/topics/train.kknn>

Principal components are orthogonal linear combinations of the descriptors. They are used here to provide a visual presentation of correlations and collinearity between descriptors which can cause instability, resulting in many combinations of descriptors providing equally good solutions. The components do not depend on flow data. Plots of principal components were prepared; the plots in Figure 4.1 below applied when eight descriptors remained, after those contributing least were eliminated. Catchments are on the left and descriptors on the right, with the two most significant components forming the x-y axes. The first component explains 40% of the variation between catchments and the second 20%.

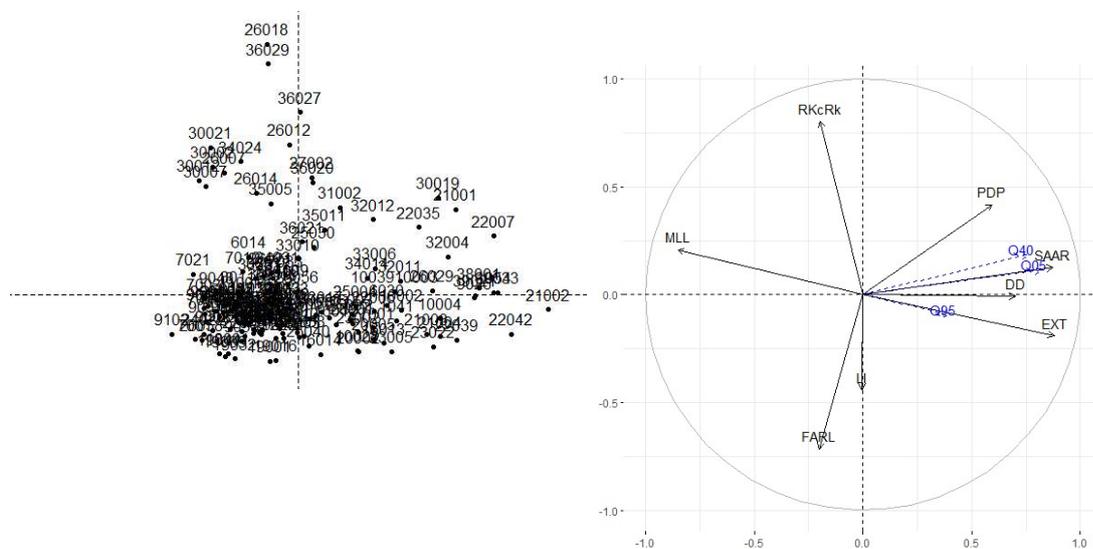


Figure 4.1 Plot of Principal Components: Catchments and Descriptors

The first component along the x-axis reflects elevation, varying from gauging station 9102 Santry River (low SAAR and low PDP) to 21002 Coomhola River (high SAAR and high PDP). Other descriptors that lie along this direction, MLL, EXT and DD were tested for elimination at the next step, in favour of SAAR and PDP. The second component, along the y-axis, strongly reflects high conduit karst RkCrk at catchment 26018 Owenure River in Roscommon and 36029 Rag River in Cavan, and lesser contributions from PDP and FARL.

Catchment FDC percentiles were superimposed onto the descriptor principal components plot, shown in blue in Figure 4.1. This indicates that, as expected, variations in Q05 and Q40 link very strongly with the first component while Q95 has a variety of contributions.

In fact, SAAR and PDP proved to be strongly significant when fitting the model, SAAR at all percentiles and PDP at most percentiles. The final stages of the process involved testing the addition of extra descriptors alongside these two, testing one additional descriptor at a time at each percentile. Table 4.2 below shows the percentage error for various model tests with one (SAAR), two (SAAR and PDP), three and four weighted descriptors in the model.

Table 4.2 Percentage Error, various Descriptors included

	<i>Mean</i>	<i>Q05</i>	<i>Q10</i>	<i>Q50</i>	<i>Q90</i>	<i>Q95</i>
1 weight	20%	30%	26%	28%	69%	91%
2 weights	20%	34%	24%	25%	53%	64%
3 weights	20%	26%	22%	22%	47%	60%
4 weights	20%	23%	20%	21%	49%	56%

The third descriptor for each percentile varied considerably for high and mid flows, but PEAT alone appeared as a strong third descriptor for low flows. There was some instability when moving to four descriptors. Therefore the number of significant catchment descriptors was finally fixed at three at all percentiles.

It is notable that PEAT is significant for the third descriptor at low flow – Q95 FSE is 56% with peat soil rather than 62% with Low Permeability subsoil, for example. The percentage of peat is already included within the second descriptor PDP, but peat’s impermeable process control of potential underground storage is particularly effective in wet blanket bog in the west. There are no natural gauged catchments in the raised bogs of the midlands. The UK Commission of Inquiry on Peatlands, Draft Scientific Review, 2010 states: “The often-repeated description of peat as a “sponge” slowly releasing large amounts of water to a stream is erroneous; a wet sponge cannot hold much additional water. Even intact blanket peat is highly productive of storm runoff very soon after rainfall, and generates little baseflow in out-flowing streams during times of low rainfall. Rainfall input is rapidly followed by a response of rising flow (discharge) in the stream, then an almost equally rapid fall back to a very low base flow level.”

4.3 Smoothing Constraints

Initially, the descriptor search was constrained by smoothing descriptor weights (and hence flows) across the percentiles. Weights were smoothed using Loess Smoothing and they were normed to give unit sum of squares of weights. The plot of the smoothed weights results for Q95 are shown in Figure 4.2.

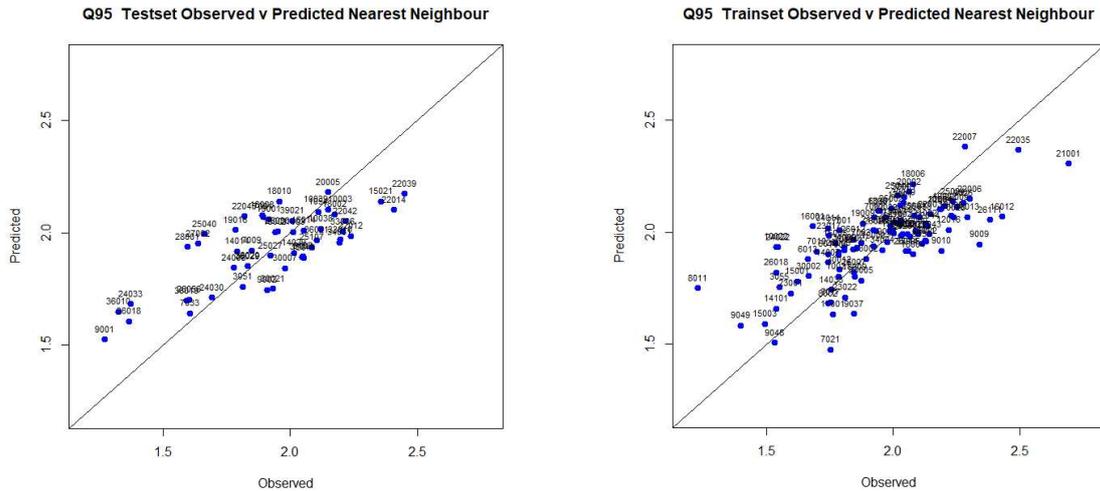


Figure 4.2 Performance of Weighted Model, Observed v Predicted Log Flow

However, it was found that a simpler smoothing method performs as well as smoothing of weights. This involves dispensing with descriptor weights in favour of no weights and smoothing the FDC itself. The procedure partitions the FDC into three bands – high, mid and low flow – across the percentiles. All percentiles in a band have the same three descriptors and hence the same pooling group. In addition to SAAR and PDP throughout, at high flows the third descriptor is karst, RKC_RK, at mid flows it is lakes FARL, and at low flows it is PEAT. Smoothing was then applied directly to the predicted FDC with little loss of accuracy. A Loess smoothing was applied using normal plotting positions; this has no effect where the curve is already smooth, that is over most of the curve, and it solves the problem when a kink might occur between the bands.

Additional minor smoothing was achieved using pooling groups with five catchments weighted by the inverse kernel, rather than the three catchments with uniform kernel of the 2009 model.

Bias and FSE were derived at each percentile using the test set catchments with pooling group members from the training set. Generally, it was found that there was little difference between the training FSE and the test FSE; this arose since the training used a crossvalidation approach among the training set and hence it has a level of independence already built in. The process of nested crossvalidation was also applied where the final Bias and FSE was calculated from ten repetitions of randomly choosing a split into training and testing sets and averaging over the ten repetitions. The Bias and FSE for annual FDCs is shown in Table 4.3 and plotted in Figure 5.1. The FSE is 56% for Q95. This will often be conservative, since model applications will have the complete set of gauging stations as potential pooling group members and furthermore, there may be a gauging station on the same river as the target site.

Table 4.3 Final Three Descriptor Model, Bias and FSE (no descriptor weights and inverse distance)

	Q0.1	Q01	Q05	Q10	Q20	Q30
1	SAAR	SAAR	SAAR	SAAR	SAAR	SAAR
2	PDP	PDP	PDP	PDP	PDP	PDP
3	RKcRk	RKcRk	RKcRk	RKcRk	RKcRk	RKcRk
Bias/FSE	2% / 49%	1% / 31%	1% / 22%	0% / 18%	1% / 17%	1% / 17%
	Q40	Q50	Q60			
1	SAAR	SAAR	SAAR			
2	PDP	PDP	PDP			
3	FARL	FARL	FARL			
Bias/FSE	1% / 18%	1% / 20%	2% / 22%			
	Q70	Q80	Q90	Q95	Q99	Q99.9
1	SAAR	SAAR	SAAR	SAAR	SAAR	SAAR
2	PDP	PDP	PDP	PDP	PDP	PDP
3	PEAT	PEAT	PEAT	PEAT	PEAT	PEAT
Bias/FSE	2% / 25%	0% / 32%	1% / 44%	4% / 56%	9% / 92%	2% / 205%

Figure 4.3 shows a plot of observed v predicted Log of flow per sqkm for Q05, Q50 and Q95.

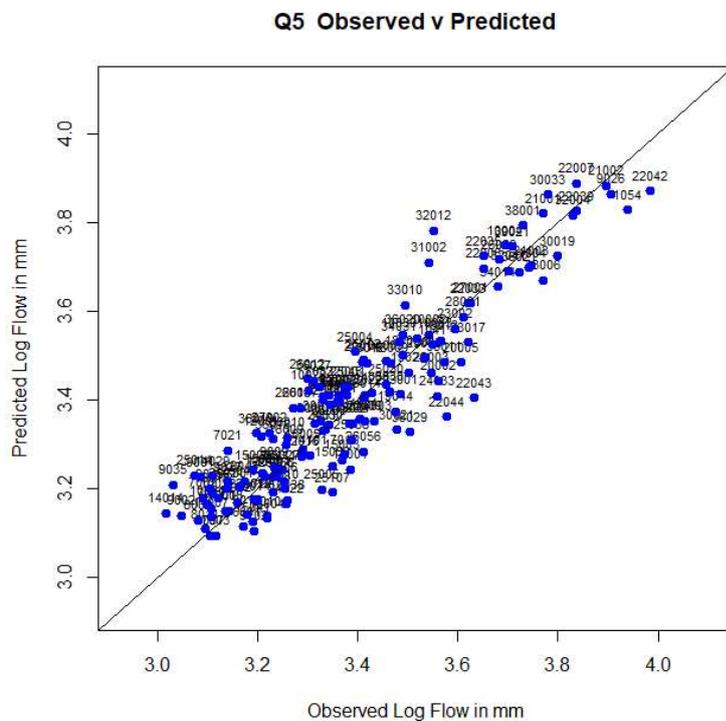


Figure 4.3a Performance of Final Model, Observed v Predicted Log Flow

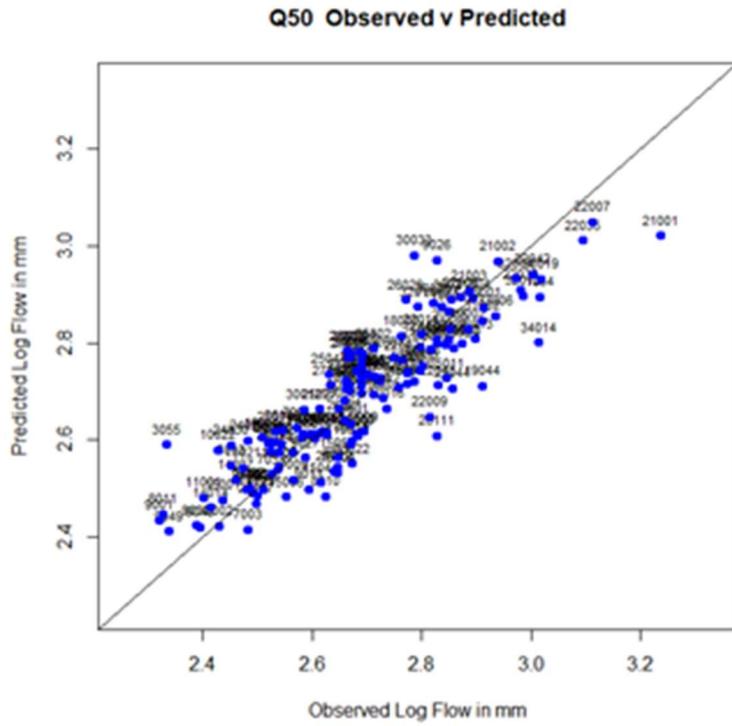


Figure 4.3b Performance of Final Model, Observed v Predicted Log Flow

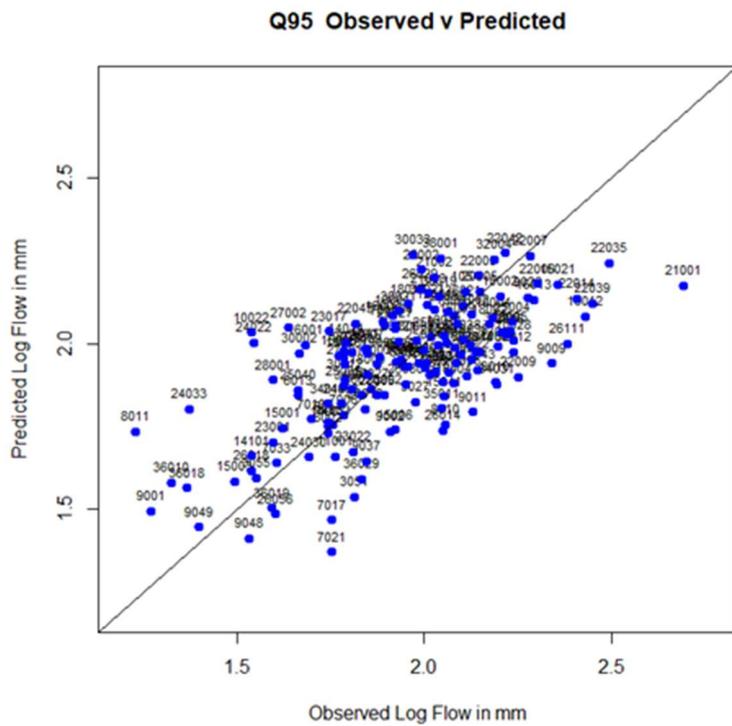


Figure 4.3c Performance of Final Model, Observed v Predicted Log Flow

5 Application of the Model

The model is applied in this section and results assessed. It is applied to estimate:

1. monthly FDCs in addition to annual FDCs,
2. annual and monthly mean flows,
3. links with surface – groundwater connectivity and
4. FDCs at all river segments across the country.

5.1 Monthly FDCs

To estimate monthly flows at a target site, the same model as the annual model was applied to gauging station monthly flows, hence the same pooling groups arose. This provided consistency between annual and monthly flows.

The resulting monthly Q95 Bias varied from 0% in November, December and January to 8% in July. The monthly Q95 FSEs varied from 33-35% in December, January and February to 84-85% in August and September. These are considered satisfactory. The results are presented in Table 5.1 and FSE is plotted in Figure 5.1.

Table 5.1 Percentage Bias / FSE

	Mean	Q05	Q10	Q50	Q90	Q95
<i>Annual</i>	1% / 16%	1% / 22%	0% / 18%	1% / 20%	1% / 44%	4% / 56%
March	1% / 16%	1% / 21%	0% / 18%	1% / 21%	3% / 32%	6% / 37%
June	1% / 28%	5% / 36%	4% / 33%	2% / 34%	6% / 54%	8% / 68%
September	2% / 31%	1% / 34%	0% / 33%	2% / 43%	2% / 65%	3% / 84%
December	2% / 15%	0% / 26%	0% / 22%	0% / 19%	0% / 31%	0% / 33%

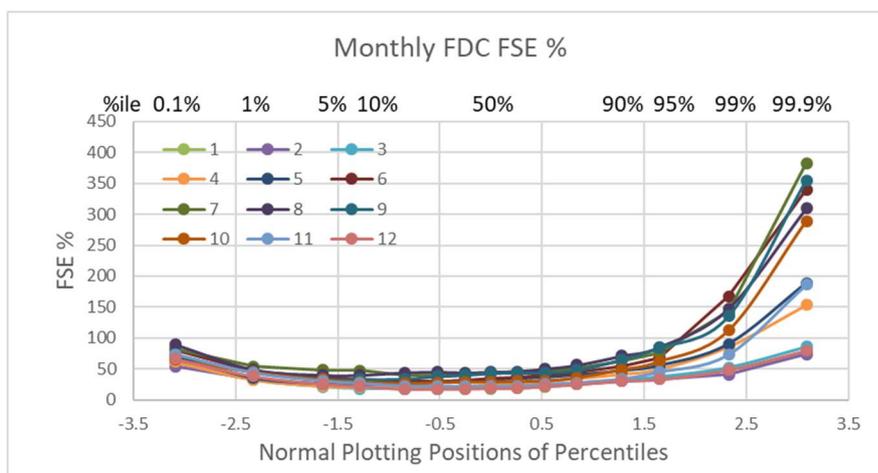


Figure 5.1 FSE for Month 1 (January) to Month 12 (December)

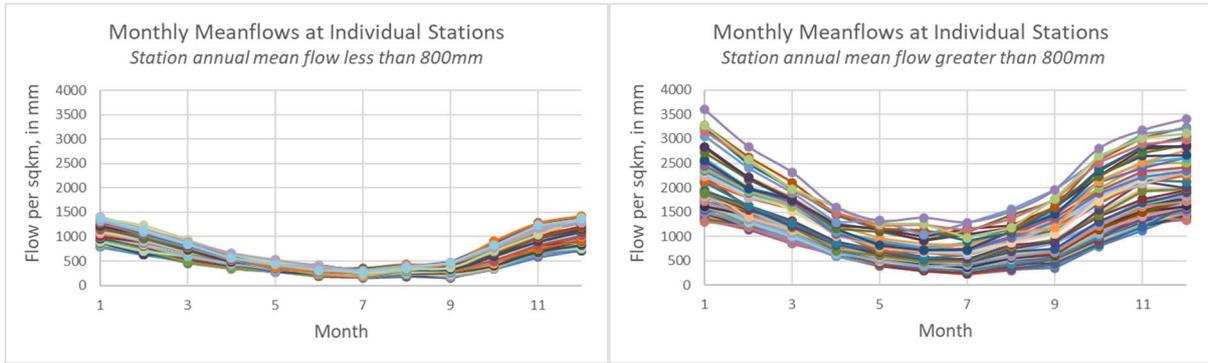


Figure 5.4 Monthly Mean Flow, stations with annual mean less than and greater than 800mm

5.3 Links with Surface-Groundwater Connectivity

FDCs have a strong linkage with catchment surface – groundwater connectivity and they are useful in representing the role of groundwater in maintaining river flow and habitats. The plot below provides a visual presentation of this link; over a common time period, it shows the water level at a spring in one of the conduit karst catchments of the FDC database and also the water level at the downstream gauging station, 30021 Robe River.

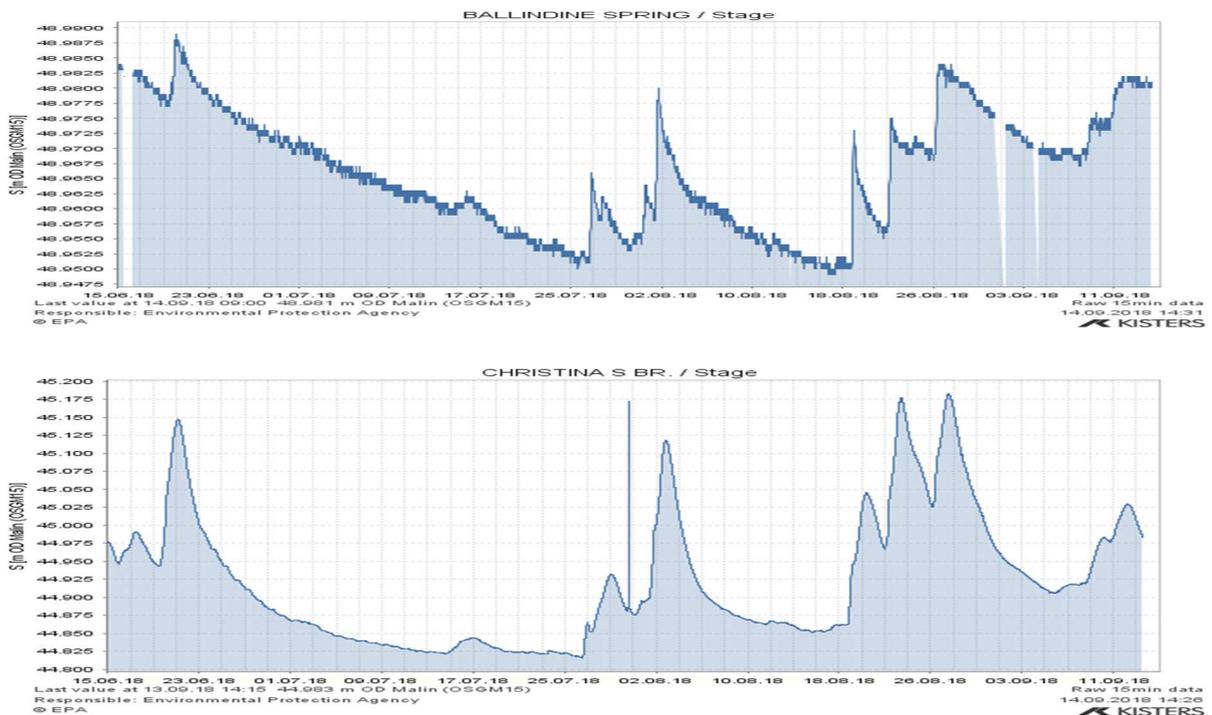


Figure 5.5 Link between Conduit Karst RKcRK and Robe River

On average, approximately 30% of the annual flow of the majority of Irish rivers is derived from aquifer recharge. Poorly productive bedrock underlies 70% of the country⁴. The low storage capacity and low

transmissivity of these bedrock aquifers means that much of the effective rainfall (rainfall less evapotranspiration) cannot be accepted by the aquifer, but instead runs off to surface water bodies. In the remaining 30% of the country, aquifer inflow is often limited by low permeability soils and subsoils overlying these aquifers. Studies of surface/groundwater connectivity have therefore focussed on caps on aquifer transmissivity and on soil/subsoil permeability. These process controls have been correlated with mapped climate and physiographic descriptors, similar to the present FDC study.

Two indices, groundwater recharge and baseflow, are considered in this context.

A recharge coefficient has been estimated across the country using a number of methods. This recharge coefficient is the proportion of effective rainfall that can *potentially* become recharge. A map of recharge coefficients was combined with an effective rainfall map and a recharge cap to produce the groundwater recharge map of the Geological Survey of Ireland¹³. The main hydrogeological properties used to generate the map were soil drainage properties, subsoil permeability and subsoil thickness. For example, groundwater flow is predicted as low in areas overlain by thick, low permeability clay, and where low permeability aquifers are not able to accept percolating waters.

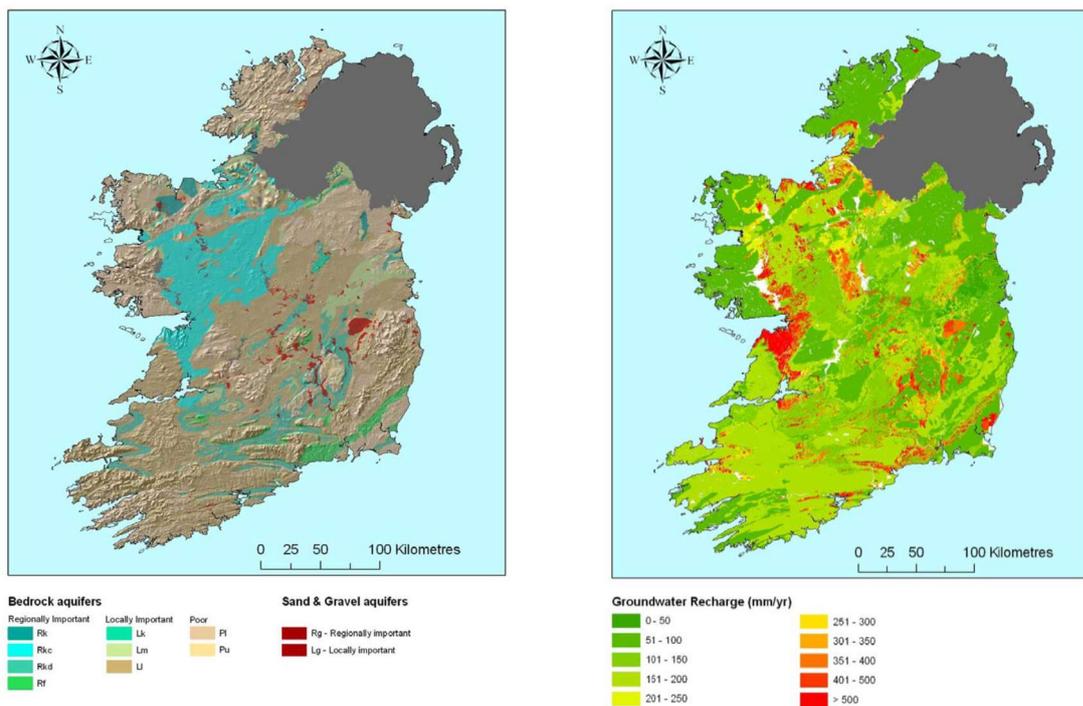


Figure 5.6 Aquifer and Recharge Maps (Geological Survey of Ireland)

The map uses a wide range of approaches including field estimates of hydraulic pathway flows applicable to different conditions as well as assessment of downstream river flows. The main factors influencing the recharge coefficient are the permeability and thickness of the subsoils; the drainage characteristics of the topsoils, the presence of peat deposits, and the presence of karst features. This is remarkably similar to the results in the present independent study for a FDC model, with its descriptors PDP, PEAT and karst RKcRK.

A stream's baseflow is a second measure, derived from river runoff. It is considered as the portion of flow that is not directly influenced by runoff from storm events. A range of methods of hydrograph separation have been developed over the years. In Ireland, baseflow varies considerably and is higher than recharge in most areas, due to the wet Atlantic climate, significant subsoil flows, storage / release from detention and banked areas following flood events, lakes, etc.

A "Baseflow Duration Curve" can be plotted alongside a FDC by applying one of the standard baseflow separation procedures to a hydrograph and plotting baseflow against percentile. The baseflow at each percentile is at or below the total river flow. At low percentiles up to about 30%ile, that is, at high flows, the baseflow curve plots well below the total flow, at mid percentiles it plots immediately below the FDC and at high percentiles, it lies directly on the FDC.

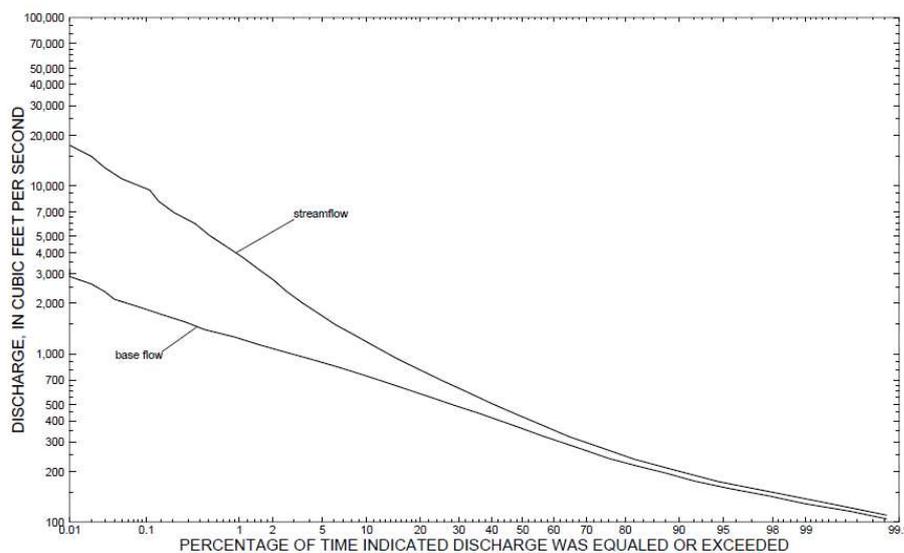


Figure 5.7 Flow and Baseflow Duration Curve ¹⁴

A Base Flow Index (BFI) was calculated from streamflow time-series in Ireland by the Office of Public Works (OPW) using the 5-day minima method and they developed an ungauged model for BFI in 2009, similar to the FDC model. This also used the Region of Influence (ROI) approach to predict the baseflow index from catchment descriptors for soils, subsoils and aquifers. It was found that BFI can be estimated from seven descriptors, the most significant of which were Well Drained soil and a new descriptor "Flatwet", which is the proportion of the time for which soils can be expected to be typically quite wet, based on soil moisture deficits. Hence this BFI model also reflects soil process control, similar to the recharge mapping and similar to the PDP and PEAT descriptors in the FDC model.

5.4 Application to National River Network

Descriptors for 19339 river segment sites across the country were prepared. The model was applied to these sites and checks for consistency were made. Annual and monthly FDCs were derived.

All available gauging stations were used when forming pooling groups. The shapes of the predicted FDCs were examined and they were acceptably smooth and monotonically decreasing. For example, those segments with lowest annual FDC slopes at each percentile are plotted in Figure 5.8. These are all located on the east coast, with low rainfall; the slopes are consistent with well-drained soils on high permeability subsoils.

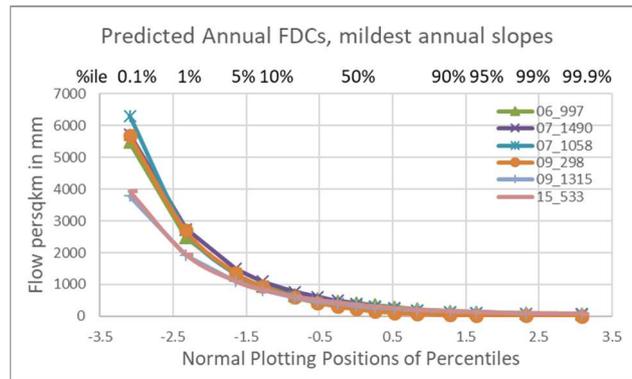


Figure 5.8 FDCs with lowest slopes

The corresponding January and July FDCs are plotted in Figure 5.9, where it is seen that these low – slope FDC shapes are consistent throughout the seasons.

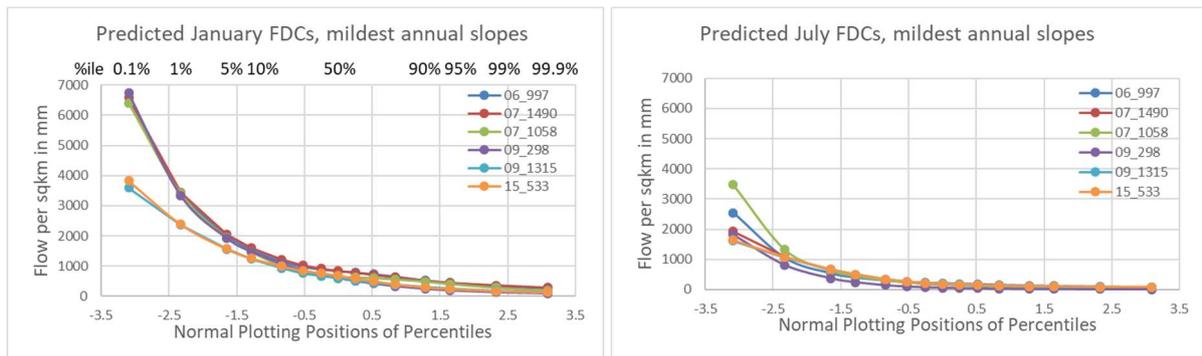


Figure 5.9 January and July FDCs with mild slopes

The varied locations and types of gauged catchments throughout the country allow the model to perform well as it forms appropriate pooling groups in this application to all major rivers and their tributaries. Those river segments whose descriptors are farthest in descriptor space from a gauging station are in relatively small mountainous peaty rivers on the west and southwest coast, with high rainfall, high slopes and no lakes. They are listed in Table 5.2. This result is considered acceptable.

Table 5.2 River Segments whose Descriptors are farthest from Gauging Stations, for low flows

Segment	Pool Members					Descriptor Distances				
31_1170	22039	1054	32004	22007	9026	1.81	1.83	1.9	1.93	1.93
31_1554	1054	22039	32004	9026	22007	1.81	1.81	1.9	1.95	1.97
31_1408	22007	9026	22039	32004	1054	1.69	1.8	1.8	1.88	1.91
31_1494	22007	9026	22039	32004	1054	1.66	1.8	1.82	1.9	1.94
31_1553	22039	1054	32004	9026	22007	1.73	1.78	1.82	1.82	1.86
31_1388	22039	1054	9026	32004	22007	1.72	1.78	1.8	1.81	1.83
31_1401	22039	1054	9026	32004	22007	1.72	1.78	1.8	1.81	1.83
31_1496	22007	9026	22039	22042	32004	1.59	1.75	1.81	1.88	1.89
31_1391	22007	9026	22039	22042	32004	1.58	1.75	1.81	1.87	1.89
31_1497	22007	9026	22039	22042	32004	1.58	1.75	1.81	1.87	1.89
21_4670	22039	9026	22007	32004	1054	1.65	1.68	1.72	1.73	1.77

Finally, a check was made that all gauging stations appear in pooling groups for nearby segments on the same river and this is the case. The model operates automatically by choosing a pooling group for the segment that includes the nearby station; this station FDC has a very high inverse distance weighting in the model and hence the estimate is always close to the gauged flow.

6 Conclusion

The 2009 ungauged FDC model has been revised and updated. The process benefitted from more recent data and a thorough review of gaps in the flow record. It also applied a more rigorous statistical procedure to arrive at a simple parsimonious model. While the same basic form of model applies, i.e. a Region of Influence method, this simple version can achieve the same and better results.

The principal component results indicated where reliable FDC - Descriptor relationships may be identifiable. Starting with SAAR, which was significant for all FDC percentiles, PDP appeared next for most percentiles. A third descriptor for each percentile varied considerably for high and mid flows, but PEAT alone appeared as a strong third descriptor for low flows. Constraining the procedure to smooth FDCs, the final model has SAAR and PDP at all percentiles with one other: RkcRK for high flows, FARL for mid flows and PEAT for low flows, giving three pooling groups across the FDC. Descriptor weights are not used. The FDC at a target site is estimated using five catchments in each group and weighting them with inverse distance kernel; then the result is smoothed.

The estimated FDC FSE error is shown below where Q95 has FSE 56%. This will be a conservative estimate in most applications. The estimated mean flow, calculated from the estimated FDC, has an FSE of 16%.

Table 6.1 FDC Factorial Standard Error

	Q0.1	Q01	Q05	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90	Q95	Q99	Q99.9
FSE	49%	31%	22%	18%	17%	17%	18%	20%	22%	25%	32%	44%	56%	92%	205%

Active descriptors in the model reflect the links between the FDC and surface – groundwater connectivity, particularly through the process control caps of PDP and PEAT, similar to the recharge and baseflow estimation methods for Ireland.

The model has been tested and validated with the dataset of annual and monthly gauging station flows and applied to 19339 river segment sites across the country, performing in a consistent manner. Monthly estimated FDCs are consistent with each other and with the annual FDCs and so also are the estimated mean flows. The monthly Q95 FSEs vary from 33-35% in December, January and February to 84-85% in August and September and the monthly meanflow FSEs vary from 15% in December and January to 39% in July.

Limitations of the model for low flows appear to be at river segments with high rainfall and peaty soil, since there are few gauging stations in these mountainous areas. Hence in this national scale model, with only three descriptors at each percentile, the possibilities for adjustment with other local information should always be considered.

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