A predictive model for estimating river habitat area using GIS derived catchment and river variables

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Running title Predictive model of river area

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Abstract

The implementation of many fisheries management related activities in fresh water depend on habitat area inventories over extensive geographical scales. While river lengths are readily available, representative widths, necessary for area calculations are difficult to obtain. As field surveys to collect this information are resource intensive, a predictive model was developed here to enable the calculation of river wetted width using GIS derived values for catchment and river descriptors. A model containing upstream catchment area and the Shreve river drainage network index accounted for 88% of the variation in field measured river wetted width. Comparisons in Irish and Scottish rivers between modelled and measured widths were highly correlated and suggest that the model may be transferable to neighbouring geographic areas. As an example the model is applied here to provide an estimate of the usable fluvial habitat available to Atlantic salmon in Ireland.

Keywords: catchment area, Shreve Index, wetted area, Ireland, Atlantic salmon, eel.

Introduction

The implementation of many fisheries management related activities in fresh water are dependent on an accurate quantification of the amounts of fluvial habitat. Such activities include the development, for example in Ireland and Norway, of conservation limits for Atlantic salmon (Prévost *et al.* 2003; Hindar *et al.* 2011). It is also required for the calculation of silver eel (*Anguilla Anguilla* L.) production across its range; a pre-requisite for the implementation of European Union wide eel recovery strategies (e.g. Aprahamian *et al.* 2007) . The extent in European rivers of habitat suitable for the survival and production of many freshwater species such as lampreys (*Petromyzon marinus* L., *Lampetra fluviatilis* L., *Lampetra Planeri (*Bloch)), crayfish (*Austropotamobius pallipes* (Lereboullet, 1858)) and freshwater pearl mussel (*Margaritifera margaritifera L.*) is required by the Habitats Directive (EC 1992). In all these cases, the use of river length as a measure of freshwater habitat is usually suboptimal; a measure of the area of available river habitat or wetted area (m^2 or ha), requiring a measure of river width in addition to length, being preferable.

The 'wetted surface of river' can be considered as the width of the water surface of a river measured at right angles to the direction of the flow during low flow conditions. The calculation of the wetted area of river in large river systems and on regional geographical scales presents a considerable technical challenge, and generally requires time consuming field survey, or the laborious extraction, if available, of river widths from aerial photography or large scale maps. A recent survey of data providers to the ICES working group on eel (WGEEL) highlighted the lack of a consistent and accurate estimates of wetted area across Europe, with many providers using digital maps of varying scales, some applying a standard width (e.g. 1 m or 5 m) and some using field survey data (ICES 2010). The lack of accurate data on the wetted area of rivers across Europe is highlighted by the fact that the most comprehensive dataset of European freshwater habitat (Catchment Characterisation and Modelling (CCM) GIS dataset) contains no data on river width (Vogt *et al.* 2007). Recently (Clerici *et al.* 2011) have used a simple model to predict river widths using the relationship between river discharge and river width across Europe (Pistocchi and Pennington 2006) in conjunction with CCM river length vectors to provide an estimate of river area size . However this approach is unsuitable for many of the applications listed above, as the CCM dataset generally only contains rivers with a stream order greater than three.

It is now possible to have desk based physical habitat measurement and assessments using map derived variables from digital aerial photography (Amiro 1993; Crozier *et al.* 2003), thus reducing the need for field surveys other than for calibration and verification purposes A predictive model developed by McGinnity *et al.* (1999 unpublished report) used a combination of nine explanatory variables obtained from digital elevation models interrogated within a GIS framework, including catchment area, river order and Rosgen classifications (Rosgen 1994) to predict wetted width. The observed data was based on stream widths collected in rivers in the North West of Ireland where high rainfall and high gradient rivers are typical. For implementation of the approach at a national scale, it was felt that a better model could be developed using a more representative national data set. It is possible that simpler catchment and river descriptors which could integrate some of the river order and gradient variables used previously would also capture some of the variation in rainfall and catchment morphology.

The main objective of the work presented in this paper, therefore, was to build a simple predictive model of wetted width to enable the calculation of the wetted surface area of a river, the inputs to which could be derived from map data through a GIS platform, and which was applicable for use across the range of hydrological and climatic conditions found in Irish rivers. The secondary objective of this paper was to provide as an illustration of the use of the model, an estimate of the accessible fluvial area (using the predictive model) available for juvenile salmon production in 173 Irish rivers.

Methods

Study sites

A total of 1,767 individual river widths in natural streams and rivers were measured in the field by Inland Fisheries Ireland personnel. The river widths were taken from a total of 340 individual river reaches (a stream reach being the section or river between confluences), located within 16 of the 40 hydrometric areas defined for the island of Ireland. At least five widths were measured for each reach using a tape measure, and in the case of some of the longer and wider reaches, 10 widths were recorded using a Bushnell® Elite 1500 laser rangefinder. The river widths were averaged for each reach. GPS coordinates for each site were also recorded, mapped and integrated into a GIS.

Model Development

Nine candidate explanatory variables were included in a multiple regression analysis in order to derive the best model for predicting river width. All the explanatory variable data were derived from GIS files developed from 1:50,000 scale digital elevation maps for all the rivers systems on the island of Ireland, except for those river systems that are wholly in the jurisdiction of Northern Ireland. These GIS files delineated and described catchment topography, river networks, river gradient, lake areas, catchment and Fisheries District boundaries. The 1:50,000 scale data were derived from the photogrammetrical analysis of aerial photography published by the Ordnance Survey of Ireland (OSI) in their Discovery Series digital maps. Software was designed specifically to transform the OSI data into the formats required for the analysis (p.mills@compass.ie). The nine candidate explanatory variables included in the analysis were: hydrometric area (Ireland is divided into 40 hydrometric areas), upstream catchment area (the area of the catchment draining into the site at which the widths had been calculated), upstream linear channel length, Strahler river network drainage index (Strahler 1952), Shreve river network drainage index (Shreve 1974), segment gradient (explain how this was calculated), minimum reach gradient, maximum reach gradient and mean reach gradient.

Statistical analysis

All variables were transformed using $Log_{10}(x)$, $Log_{10}(x+1)$ or $\sqrt[3]{(x+0.0001)}$ where necessary, to ensure that data were normally distributed. A multiple linear regression was used to identify the combination of those explanatory variables that best described the variation in measured wetted width. Analysis was carried out in Brodgar version 2.5.0 (www.brodgar.com), which is a front end interface for the statistical package R (http://www.r-project.org). Backwards and forwards selection was used to eliminate non-significant variables, and the best fit model was determined by the AIC value (Akaike Information Criteria).

The final wetted width regression relationship sought to minimise the sum of the squared errors of the prediction. In order to determine the standard error of this prediction, the square root of the average squared error of the regression predictions was used (Lane 1999). This was calculated using the residuals from a linear regression between $\log_e$ transformed empirical river width measurements and $\log_e$ transformed widths for the same site estimated using the wetted area regression:

$$SE_{est} = \sqrt{\frac{\sum (Y - Y')^2}{N-2}}$$

where SE_{est} is the standard error of the estimate, Y are residuals from the linear regression between $\log_e$ transformed empirical river width measurements and $\log_e$ transformed widths for the same site,

Y' are the values predicted from the regression between $\log_e$ transformed empirical river width measurements and $\log_e$ transformed widths for the same site, and N is the number of pairs of (X,Y) points.

The predicted wetted width model was tested against 2 sets of wetted width data collected using more standard methods. The first dataset were widths measured from high resolution aerial photography of the Burrishoole catchment in North West Ireland. The aerial photographs were taken from an average height of 984m, and were radiometrically balanced and geo-rectified to Irish National Grid projection to produce a typical resolution of 15-25cm. The mosaic of aerial photographs were analysed using ARC GIS 9, and five wetted widths for each reach of river within the Burrishoole catchment was measured at a scale of 1:300. The aerial photographs were taken on the 12th April 2007, when water flow in the Burrishoole catchment was low. The second dataset used to ground truth the predictive model comprised 28 wetted widths measurements of the North Esk River in Scotland, taken from a high resolution, survey based map of the UK (Urban areas 1:1,250, rural areas 1:10,000) (Ordnance Survey 2007).

Extrapolation of wetted area model predictions to Irish salmon rivers

Regional fisheries personnel provided information on those waters which hold, or which had previously held biologically significant salmon populations. In addition, parts of these individual river systems that could not be accessed by adult salmon based on information again provided by fisheries personnel were mapped (McGinnity *et al.* 2003). First order streams (the first streams from the watershed line identified on the 1:50,000 Discovery series) were not included in this analysis, as they are generally not considered to be of major importance with regard to salmon production. Multiplication of the predicted wetted widths with the GIS derived length of reaches from the Irish Ordnance Survey river network was applied to determine the surface area of reaches within each river. The fluvial habitat area for each river catchment was then determined by network analysis. The downstream geographical starting point for the network analysis of each river system was the point located at the coastal 'High Water Mark'. Limits to the extent of the area of river channels used by salmon was determined dynamically during the network analysis by cross-reference to locations previously determined and recorded in a 'Barrier' data set (McGinnity *et al.* 2003). This 'Barrier' data set recorded the location of: 1) impassable barriers; 2) points above which the channels are not utilised by salmon; 3) points above which the river containing salmon is considered to be 'non self sustaining' due to the presence of impounding dams and electricity generating facilities. Lake surface areas for each river catchment were also measured from the Ordnance survey 1:50,000 scale maps, and combined with modelled wetted areas for rivers to produce a total wetted area for salmon production for each Salmon River in Ireland. A total of 173 rivers were included in this extrapolation, based on an initial identification of 'salmon' rivers (McGinnity *et al.* 2003) in Ireland. This list of 173 rivers has subsequently been amended to 148 Irish rivers (Anon. 2009), however for the purposes of this exercise we provide the assessment or river area for the original 173.

Results

The best model to predict wetted width of rivers included two explanatory variables: upstream catchment area and Shreve index (Table 1). These two variables explained 88% of the variation in the wetted width measured in the field using the equation:

$$\mathrm{Log}_{10}(\text{Wetted width} + 1) = 0.22734 + 0.20045\ (\log_{10} \text{catchment area}) + 0.25939\ (\log_{10} \text{Shreve index})$$

While the predictive capacity of this model seems to be very good for most river sites using the full dataset, it underestimates widths at larger sites (widths > than 40m) (Fig. 1). There was a strong correlation between the results of the predictive model and remote measurements of wetted width for the Burrishoole and North Esk river systems (Pearson product correlation coefficient of 0.93 and 0.91 respectively, n = 90 and 28, $p<0.01$ in both cases, data were square root transformed) (Fig. 2). However, as with the full dataset, the model tends to underestimate widths at wider reaches (>25 m) in the North Esk system.

A quantitative estimate of the area (in hectares) of river and lake habitat in Ireland that could potentially be used by salmon is presented for each of Ireland's 17 Fisheries Districts (Table 2). The location of the Fisheries Districts is shown in Figure 3. A total fluvial habitat of 14,759 ha is estimated nationally using the model described above. Within salmon rivers, the analysis estimates that 83% or 12,198 ha is accessible to migratory fish. Of the 17 Fisheries Districts, the Waterford District has the greatest quantity of accessible fluvial habitat (2,856 ha) available for juvenile salmon production or 23% of the national accessible habitat. A total of 105,777 ha of lake habitat was identified in the 17 Fisheries Districts (Table 1). Of this lake habitat, 44,745 ha is available to salmon. The Galway District accounts for 40% of the accessible lake habitat available.

Data are provided on total and accessible fluvial and lake habitat on an individual river system basis for each of the 173 rivers in Ireland (Supplemental information). Four river catchments, the Shannon, Erne, Lee, and Liffey, have large hydropower installations (Fig 3). The fluvial wetted area above these four installations is estimated to be 1,966 ha, which is 13% of the total fluvial habitat. The lacustrine wetted area above the four installations is 47,437 ha, approximately 45% of the total lacustrine habitat in Ireland. The River Suir in the Waterford District has the largest quantity of accessible fluvial habitat of any salmon river nationally (1,038 ha), 8.5 % of the national accessible total. The largest twenty rivers in terms of accessible wetted area contain 71 % of the total accessible fluvial salmon habitat in Ireland (Figure 3).

Discussion

The predictive model described in this paper provides a very simple and useful tool for the quantification of the freshwater habitat resource in Ireland and perhaps could be applied in other countries. The strong correlation between the predicted and map measured widths of the North Esk in Scotland suggests that the model may be transferable to neighbouring geographic areas with comparable meteorological and topographical conditions and where similar relationships between ground water, catchment area and Shreve index would be expected. Considerably fewer resources are required to calculate catchment area and Shreve indices for river basins from GIS layers than those required to either acquire directly measures of habitat from aerial photography or from empirical field measurements, so the model approach presented here represents a cost effective method of estimating freshwater habitat over extensive geographical areas.

It should be noted that the raw data used to produce this predictive model did not include first order streams as the original motivation for the exercise was to provide data for salmon management. It remains to be tested whether the same relationship between catchment area, Shreve index and wetted width exists for these smaller streams. In calculating the wetted area of habitat for other species, such as eel, lamprey, trout and crayfish, additional quantification of the wetted area of first order streams may be required. For example, a standard width of 0.8 m was assigned to first order streams across Ireland, in order to quantify the area of fluvial habitat accessible to eel in Ireland (Compass Informatics in press). This quantification was combined with the results from the predictive model described in this paper to provide a total wetted area for Irish rivers. Based on this assumption, it was estimated that first order streams represented approximately 10% of total fluvial habitat in Ireland.

Additional work is also required to increase the accuracy of the predictive model at wider river reaches. Potential explanatory variables that might account for the underestimation of widths at the lower reaches of large rivers (e.g. Fig 2, North Esk) include the presence and extent of large lakes, flood control measures, impoundments and drainage programs. It is possible that the latter three factors do not lend themselves to predictive modelling, as their extent and design is determined by human, rather than natural hydro-morphological processes. In this case, field based measurement, or use of aerial photography on a targeted basis in problem locations may need to be employed to get an accurate wetted width or in the case of arterially drained channels the design widths may be available from drainage authorities; much of this archive information is available in GIS format. The dataset complied by Pistocchi and Pennington (2006) may also be useful for these larger sites; a comparison between the outputs from Clerici et al (2011) and the model presented here could be undertaken. It is worth noting that only 285 of the 42098 river segments in the Irish rivers assessed were predicted to have wetted widths greater than 40m, so underestimating the widths of these segments is unlikely to change the national accessible area for salmon significantly.

This paper presents a first step methodology for quantifying river habitat area over extensive geographical scales. In order to assess whether particular rivers are meeting their productive potential, additional habitat quality variables may be needed. These might include hydro-morphological factors such as altitude, slope, and distance from source (Schmutz *et al.* 2007), and water quality indicators such as such as macroinvertebrate indices and water chemistry (Kelly *et al.* 2007). The partitioning of the total wetted area based on these factors would allow problem areas to be identified, and ameliorative measures to be implemented where appropriate. The results presented here identified a significant amount of the freshwater habitat in Ireland as not being capable of sustaining natural salmon populations because of the presence of large hydropower stations, particularly in the Shannon catchment. Although these installations are technically passable (there are inbuilt fish passes) by adult salmon, they are not considered to be effective in maintaining self-sustaining salmon populations (Mathers *et al.* 2002). To bring this significant resource into production, fish passage difficulties, particularly relating to smolt migration, need to be resolved.

The outputs of this wetted area quantification for rivers are currently being used in Ireland (Anon. 2010) to identify individual river salmon management reference points using the Bayesian Hierarchical Stock and Recruitment Analysis (BHSRA) developed by Prevost *et al.* (2003). The BHSRA is derived from a set of 13 stock and recruitment data series from monitored salmon rivers located in the Northeast Atlantic, to enable the transportation of stock and recruitment information between data rich and data poor rivers and to set conservation limits (CLs) accordingly. Notably, for the use of this model, no information is required on the specific habitat quality (e.g. gradient, water quality, spawning areas) of these data poor rivers, as the model yields a set of useful biological reference points, using only the size of the river (e.g. the usable wetted area) and the rivers latitude (Prévost *et al.* 2003; Ó'Maoiléidigh *et al.* 2004; Crozier *et al.* 2003).

Habitat area quantification is a fundamental requirement for conservation management. We envisage that this model and its outputs will be used for a wide range of management applications in fresh water and for many fish species, such as the implementation of the Habitats directive in rivers (EC 1992), the EU regulation on establishing measures for the recovery of the stock of European eel (EC 2007), as well as the already implemented conservation program for Atlantic salmon in Ireland (Anon. 2010).

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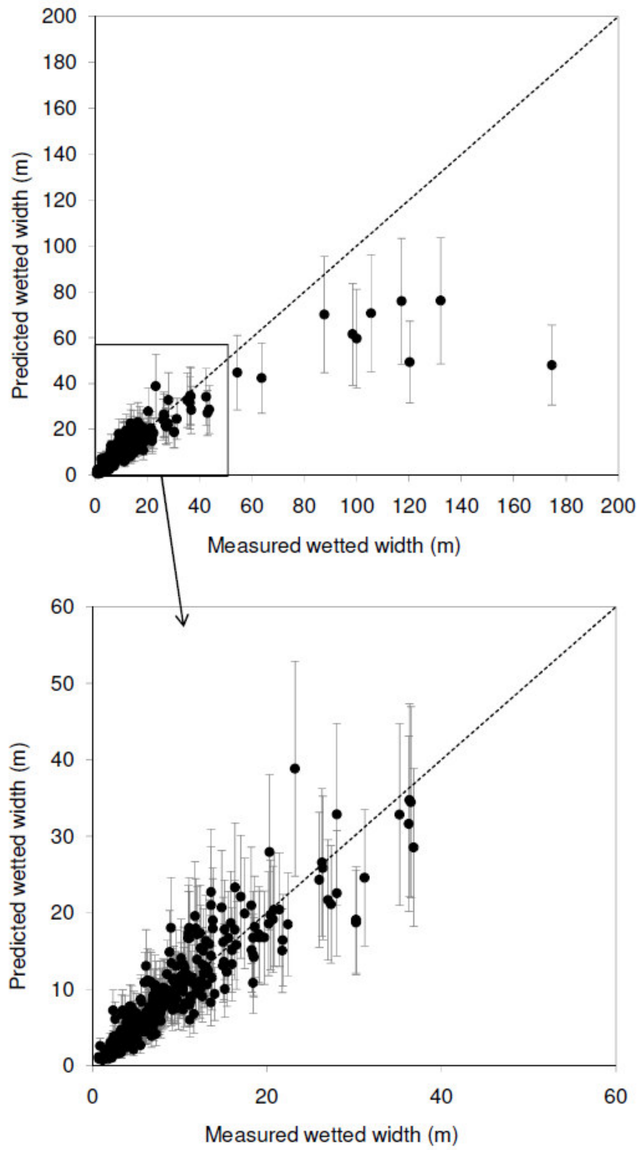

Fig. 1. Measured and modelled wet widths for 340 river sites in Ireland. Wet widths were measured using tape measures, while modelled wet widths were calculated using the formula: $\text{Log}_{10}(\text{Wet width} + 1) = 0.22734 + 0.20045\ (\log_{10} \text{catchment area}) + 0.25939\ (\log_{10} \text{Shreve index})$. Error bars indicate the standard error of the estimate, and the dashed line indicates a relationship with a pearson product correlation coefficient of 1.

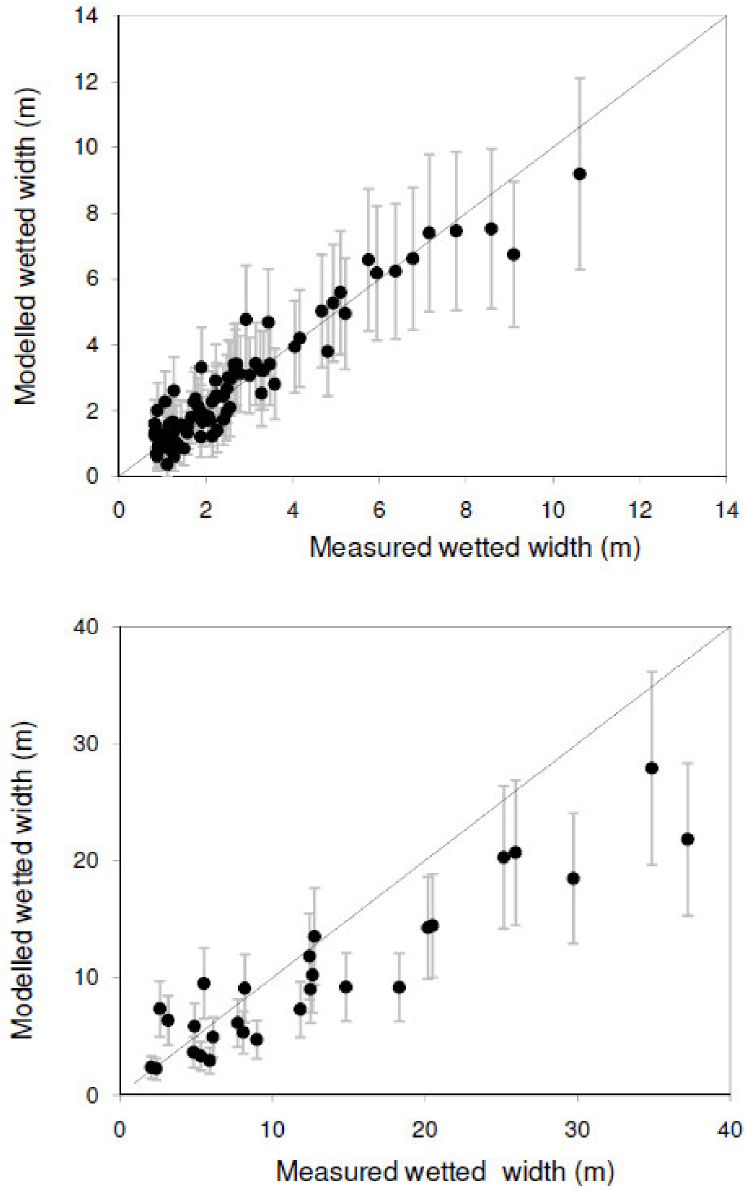

Fig. 2. Correlation between measured and modelled wet widths for the Burrishoole (top) and North Esk (bottom) catchments. The dashed line indicates a relationship with a pearson product correlation coefficient of 1. Widths were measured from aeriel photography (Burrishoole) or high resolution maps (North Esk). Modelled wet widths were calculated using the predictive model: $\text{Log}_{10}(\text{Wet width} + 1) = 0.22734 + 0.20045\ (\log_{10}\text{catchment area}) + 0.25939\ (\log_{10}\text{Shreve index})$.

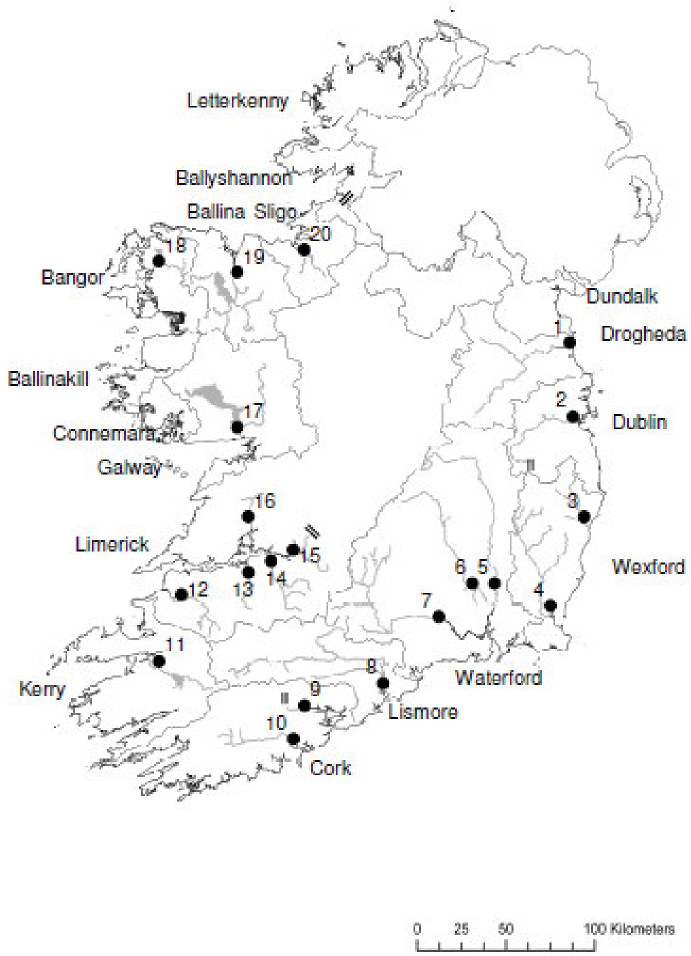

Figure 3. Map of the 17 Irish Fisheries Districts showing the location of the twenty rivers with the largest amount of accessible wet area for salmon production. Parallel lines on four rivers (Liffey, Lee, Shannon & Erne) refer to hydroelectric dams above which salmon populations are considered not self-sustaining. Rivers marked 1 to 20 are: (1) Boyne, (2) Liffey, (3) Avoca, (4) Slaney, (5) Barrow, (6) Nore, (7) Suir (8) Blackwater, (9) Lee, (10) Bandon, (11) Laune, (12) Feale, (13) Deel, (14) Maigue, (15) Shannon, (16) Fergus, (17) Corrib, (18) Owenmore, (19) Moy & (20) Ballysadare.

Table 1. Best fit model explaining the response variable, Log_{10} (wetted width +1), using multiple linear regression of explanatory GIS derived variables

ANOVA

	d.f.	Sum Sq	Mean Sq	*F*	*p*
Log_{10} Catchment Area	1	29.67	29.67	2223.13	<0.0001
Log_{10} Shreve	1	1.82	1.82	136.10	<0.0001
Residuals	321	4.28	0.01		

Adj. R^2 = 0.88

F = 1180 (2, 321 d.f.)

p<0.0001

Coefficients

	Estimate	Std. error	*t*-value	*p*
Intercept	0.22734	0.01721	13.21	<0.0001
Log_{10} Catchment Area	0.20045	0.01891	10.60	<0.0001
Log_{10} Shreve	0.25939	0.02224	11.67	<0.0001

Table 2. A quantitative estimate (ha) of the national salmon river and lake habitat resource in Ireland presented on a Fisheries District basis. Total fluvial habitat refers to all wetted area (ha) of riverine channel for the 173 salmon rivers, up to the tidal limit, (excluding 1st order streams), within a Fisheries District. Accessible fluvial habitat refers to the extent of channel into which salmonids can migrate freely up to the first impassable barrier. Similarly total lacustrine habitat includes the total surface area (ha) of lakes within the identified salmon rivers in a District. Accessible lacustrine habitat includes those lakes within a District that can be used by salmon.

Fisheries district	Total fluvial habitat (ha)	Accessible fluvial habitat (ha)	Total lacustrine habitat (ha)	Accessible lacustrine habitat (ha)
Ballina	927	886	7412	6985
Ballinakill	181	168	1302	1100
Ballyshannon	886	309	9367	2983
Bangor	293	283	1835	1835
Connemara	78	72	1802	1732
Cork	724	482	1402	131
Drogheda	783	783	1322	1322
Dublin	479	354	2303	67
Dundalk	347	341	159	159
Galway	895	594	28320	17747
Kerry	843	814	5852	5661
Letterkenny	508	478	2045	1939
Limerick	2647	1531	39219	1050
Lismore	1070	1068	3	3
Sligo	390	369	3200	1950
Waterford	2883	2856	35	35
Wexford	825	811	197	44

National Total	14759	12198	105777	44745