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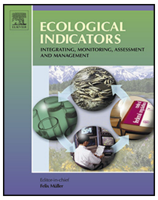

Mapping habitat indices across river networks using spatial statistical modelling of River Habitat Survey data

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ABSTRACT

Freshwater ecosystems are declining faster than their terrestrial and marine counterparts because of physical pressures on habitats. European legislation requires member states to achieve ecological targets through the effective management of freshwater habitats. Maps of habitats across river networks would help diagnose environmental problems and plan for the delivery of improvement work. Existing habitat mapping methods are generally time consuming, require experts and are expensive to implement. Surveys based on sampling are cheaper but provide patchy representations of habitat distribution. In this study, we present a method for mapping habitat indices across networks using semi-quantitative data and a geostatistical technique called regression kriging. The method consists of the derivation of habitat indices using multivariate statistical techniques that are regressed on map-based covariates such as altitude, slope and geology. Regression kriging combines the Generalised Least Squares (GLS) regression technique with a spatial analysis of model residuals. Predictions from the GLS model are 'corrected' using weighted averages of model residuals following an analysis of spatial correlation. The method was applied to channel substrate data from the River Habitat Survey in Great Britain. A Channel Substrate Index (CSI) was derived using Correspondence Analysis and predicted using regression kriging. The model explained 74% of the main sample variability and 64% in a test sample. The model was applied to the English and Welsh river network and a map of CSI was produced. The proposed approach demonstrates how existing national monitoring data and geostatistical techniques can be used to produce continuous maps of habitat indices at the national scale.

1. Introduction

Freshwater ecosystems represent less than 1% of the Earth's surface and 10% of all known species, yet they are declining faster and are more endangered than their terrestrial or marine counterparts, partly because of physical pressures on habitats and species (Loh et al., 2005; Revenga et al., 2005; Strayer and Dudgeon, 2010; Vorosmarty et al., 2010; WWF, 2014).

Although research in ecology and environmental management has grown substantially in the past half-century, it has mainly focused on post-industrial issues such as water quality, pollution and land use impacts (Vaughan et al., 2009). With gradual improvement in water quality, other limiting factors such as physical habitat quality (i.e. the naturalness of the flow of water, and the structure and composition of the river bed and banks) and connectivity have become prominent.

Globally, degradation of physical habitat quality due to river engineering and associated activities (e.g. constructions of dams, bridges, concrete banks, dredging) is recognised as a major conservation issue (Collen et al., 2014; Sala et al., 2000; Tockner and Stanford, 2002; World Conservation Monitoring Centre, 1998). In Europe, as part of the implementation of the Water Framework Directive (WFD), member states must assess the ecological condition of rivers and lakes based on the naturalness of a series of biological elements (European Union, 2000). Following the first

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round of River Basin Management Planning, 56% of water bodies failed to achieve their ecological targets. Engineered structures and 'altered habitats' were the dominant pressures responsible for the failures, ahead of point and diffuse sources of pollution (European Environment Agency, 2012). In England and Scotland, the proportion of water bodies failing to achieve ecological targets because of physical alterations was 49% and 37%, respectively (Environment Agency, 2012). The WFD requires member states to mitigate or remove impacts on habitats and species through the implementation of programmes of measures including river restoration.

The effective management of habitats at national and local scales should ideally be based on some knowledge of their distribution and an assessment of their naturalness and accessibility. At present, in Great Britain, habitats are either surveyed using semi-quantitative methods at randomly selected sites that do not allow for continuous assessments or using habitat mapping techniques over longer stretches of river (Maddock, 1999). Habitat mapping is geographically limited and generally carried out on an ad hoc basis by experts during 'walkover surveys' where habitat features are recorded on maps using mobile Geographic Information System (GIS) or hand-drawn sketches and some broad typologies (Hendry and Cragg-Hine, 1997; Sear et al., 2009). Although such methods provide valuable information on habitat distributions over relatively small areas, they are likely to be too expensive to implement across entire networks. The reliance on expert judgement for assessing habitat types and boundaries may also generate between-surveyor variability in the outputs produced and, as notions of habitat structure evolve, data collected at one point in time may not be comparable to maps produced years later by different experts (Cherrill and Mcclean, 1999).

An alternative approach is to use river typologies based on geomorphological templates to predict the occurrence of broad river types along the river continuum. The history of attempts to classify rivers into different types spans at least 125 years, a period over which perhaps a hundred if not more individual efforts to divide and categorise rivers have been made (reviews of the extent of such efforts are given by Downs, 1995; Montgomery and Buffington, 1997; Mosley, 1987; Naiman et al., 1992; Newson et al., 1998; Thorne, 1997).

Most river classification systems are based on the identification of river types using a few key variables representing drivers of geomorphological change or river processes such as stream power, sediment transport and supply (Montgomery and Buffington, 1997; Newson et al., 1998; Rosgen, 1994). Although relationships between expert-driven geomorphic types and GIS attributes such as slope and drainage area can be observed, there is a considerable amount of overlap between types, reflecting the potential influence of additional driving elements such as channel, bank and hillslope vegetation, climate, woody debris, and natural variability in channel process expression (Church, 2002; Montgomery and Buffington, 1997; Rosgen, 1994). Greater differentiation between river types can be achieved by introducing attributes recorded in the field such as relative roughness (Montgomery and Buffington, 1997), shear stress or channel substrate (Rosgen, 1994), but this implies that extensive field work is carried out, thus reducing the feasibility of such an approach at national scales.

In this article, we propose an alternative approach for mapping habitat elements across entire river networks that does not require continuous surveys of river catchments, but makes use of existing semi-quantitative survey data, GIS and a geostatistical technique called regression kriging (RK). The principle of the method is to identify and define habitat indices representing major dimensions in habitat distribution using known equations, expert systems or multivariate statistical analysis applied to existing habitat data taken from national surveys or monitoring programmes. The habitat indices are then predicted using Generalised Least Squares (GLS) linear regression models using GIS map-derived covariates such as altitude, slope, distance from source, discharge and geology which represent the known drivers of habitat/geomorphological change. The model residuals are then analysed using geostatistical functions to identify any remaining spatial correlation and pattern in their distribution. In the presence of spatial correlation, an interpolation method, called kriging, is applied to account for (and, thus remove) any spatially correlated residual variance such that the interpolated residual predictions can be added to the GLS regression predictions. The RK model can then be applied to the entire river network by deriving the GIS covariates at regular spatial intervals (e.g. 500 m).

This paper reports the development and application of the statistical models to a key and poorly mapped habitat element – channel substrate. Channel substrate is a key component of species habitat (Maddock, 1999; Townsend and Hildrew, 1994), and it is one of three elements defining morphological condition under the WFD (European Union, 2000). Channel substrate is also linked to the wider issues of diffuse pollution and agricultural impacts and it is key to our understanding of river and catchment processes (Collins et al., 2012; Rosgen, 1994).

2. Material and methods

2.1. Index derivation

River Habitat Survey (RHS) data was used to derive an index representing channel substrate. RHS is a CEN-compliant (CEN, 2004) standard methodology for hydromorphological assessment under the WFD that is used in the UK and across Europe (Raven et al., 1997). It is a methodology for recording habitat features for wildlife that has been implemented at more than 25,000 sites in the UK since 1994. From 1994 to 1996 and from 2007 to 2008, surveys were carried out at random sites in every 10 km^2 in England and Wales, thus, ensuring a wide geographical coverage of the river network.

RHS records the presence of natural and management features at 10 equally spaced transects or 'spot-checks' along a 500 m reach (Raven et al., 1997). A visual estimate of the dominant channel surface substrate classified into eight categories according to the Wentworth scale (Wentworth, 1922) is recorded at each spot-check. The substrate types recorded (with acronyms in brackets) are bedrock (BE), boulder (BO), cobble (CO), gravel-pebble (GP), sand (SA), silt (SI), clay (CL) and peat (PE). When channel substrate is not visible because of depth, water turbidity or the presence of a culvert, surveyors record the substrate type as 'Not Visible' (NV).

RHS spot-check data on channel substrate was tabulated for all existing sites, each row representing a site and each column a substrate type (including 'Not visible'). The channel substrate spot-check table was analysed using Correspondence Analysis (CA). CA is a multivariate analytical technique similar to Principal Component Analysis that is applicable to contingency tables (i.e. tables of counts). CA performs an analysis of the total table inertia and extracts dimensions (or components) representing linear combinations of input variables based on the amount of total inertia explained. Only sites in Great Britain were used as GIS datasets were not available for Northern Ireland at the time of the analyses.

To derive the index, we used a subset of 2680 semi-natural RHS sites (i.e. sites with few or no in-channel bank structures or modifications) to reduce the potential influence of modifications on natural channel substrate diversity (Raven et al., 1997). Missing ('Not Visible') values were added as an additional variable in the analyses to account for differences in survey counts when present. The resulting dimensions were investigated for their ecological and