The use of spatial information to improve hydrometric network design and evaluation

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Abstract Operational needs commonly dictate the evolution of hydrometric networks. Such an approach can fail to meet strategic water management information objectives (e.g. to estimate flows at ungauged sites, to detect hydrological change). This paper examines the role of digital spatial information to inform network evolution. Capitalising on a range of catchment physical descriptors and spatial characteristics commonly used in hydrological studies, the UK National River Flow Archive (NRFA) developed two indices that assess the strategic value of individual gauged catchments, independently from the performance of the associated gauging station. The Representative Catchment Index (RCI) quantifies how representative a catchment is of a specified area, in relation to a selection of spatial characteristics. The Catchment Utility Index (CUI) examines the influence of individual catchments in the context of a regionalization methodology used for flood estimation. A large UK catchment is used as a case study to demonstrate how these indices can support network reviews.

Key words hydrometric network; hydrometry; network management; network rationalization; regionalization; representative catchment; spatial information

INTRODUCTION

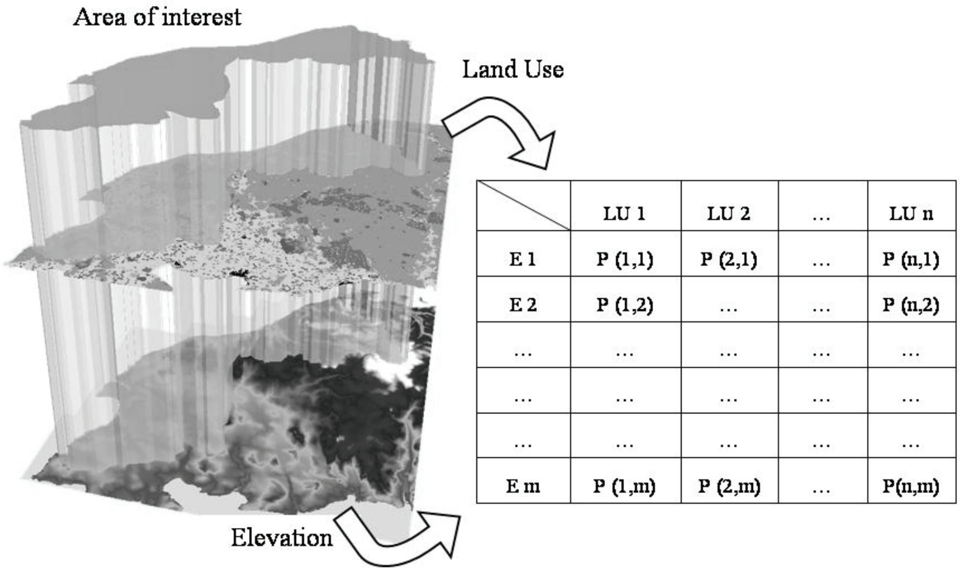
Hydrometric data are the foundation of water management and gauging station networks throughout the world and service a rapidly growing need for river flow data. However, many networks are in decline due to funding, technical and institutional constraints triggering reductions in flow measurement capabilities and gauging station densities in many parts of the world (Vörösmarty, 2002).

Conceptually, hydrometric networks should evolve to address both operational and, increasingly, more strategic needs, e.g. to estimate flows at ungauged sites (Thomas, 1994) and to detect hydrological change (Kundzewicz & Robson, 2004). Yet, in practice, most reviews of networks focus principally, if not exclusively, on assessing how well individual stations meet operational requirements (e.g. flood warning, resource assessment, river regulation), and do not take into account their strategic value.

Significant research effort has been devoted to optimizing hydrometric networks and maximizing their information delivery. Network appraisal mechanisms have evolved from simple gauging station density guidelines based on physiographic regions (World Meteorological Organization, 1994) to more sophisticated statistical analyses, e.g. using both catchment physiography and flow characteristics, or focusing on the information content of the flow record (see Markus *et al.*, 2003). This paper examines the approach taken by the UK National River Flow Archive (NRFA) that, unlike the aforementioned techniques, relies specifically on spatial characteristics to assess the strategic value of individual gauged catchments, independently from their associated gauging station.

Despite the increasing availability of digital geodatasets, which is widely capitalized on in regionalization procedures, there have only been a few studies (e.g. Black *et al.*, 1994) exploring the potential of spatial information to inform network evolution. Capitalizing on a wide range of catchment physical descriptors (e.g. size, average rainfall) and spatial data sets (e.g. elevation, land use), the NRFA developed two indices: the Representative Catchment Index (RCI) and the Catchment Utility Index (CUI). Both are used by the NRFA to review the UK gauging station network.

In the UK, hydrometric data from the various measuring authorities are collected by the NRFA, which maintains a comprehensive database of river flows totaling approximately 45 000 years of records. In this paper, the UK gauged network comprises 1236 gauging sites, for which catchment boundaries and spatial information have been derived. After a brief presentation of both indices, the assessment procedures used by the NRFA are demonstrated in a case study focusing on a single gauged catchment.



	LU 1	LU 2	…	LU n
E 1	P (1,1)	P (2,1)	…	P (n,1)
E 2	P (1,2)	…	…	P (n,2)
…	…	…	…	…
…	…	…	…	…
…	…	…	…	…
E m	P (1,m)	P (2,m)	…	P(n,m)

Fig. 1 Example of the integration of two spatial data sets to characterize an area of interest (e.g. catchment) as a bi-dimensional matrix storing the proportion of any combination of datasets occurring within the analysis mask.

REPRESENTATIVE CATCHMENT INDEX

The WMO recommends that hydrometric networks should include at least one gauged catchment that is representative of each region where hydrological similarity is presumed (Toebes & Ouryvaev, 1970). The RCI (Laizé, 2004) quantifies how representative a catchment is of a reference area, in relation to a selection of spatial characteristics. First, using a Geographical Information System (GIS), raster data sets are integrated in order to characterize the relationship between spatial data sets within the catchments and reference areas. The boundary of an area of interest is used as an analysis mask, i.e. all operations are constrained to the points located within this area. For each location within the mask, the corresponding raster values are extracted. Each area is described by a matrix storing the proportion of any combination of characteristics occurring within the area. This is illustrated in Fig. 1 using two characteristics. Once a selection of catchments and a reference area have been processed, the catchment matrices are compared to the reference matrix on a cell-by-cell basis in order to calculate the catchments' RCI, ranging from 0 (no match) to 100 (identical matrices). The resultant score allows for the ranking of the catchments relative to each other. For this study, the RCI implementation used three characteristics: elevation, land use, and soil type.

CATCHMENT UTILITY INDEX

The CUI is based on procedures developed for the UK *Flood Estimation Handbook* (FEH; Institute of Hydrology, 1999). The FEH capitalizes on a digital terrain model (DTM) of the UK (Morris & Flavin, 1990), which was designed to be consistent with the drainage network and allows the boundaries of around four million catchments to be derived. Catchment descriptors have been automatically generated for those catchments whose area exceeds 0.5 km^2.

To estimate flood peaks at an ungauged site, the FEH combines data from a number of stations—usually 20 for a 100-year return period—whose catchments are similar to that of the target site in terms of size, wetness, and responsiveness. These characteristics are expressed as three catchment descriptors: Area, Standard-period Average Annual Rainfall (SAAR), and Base Flow Index (BFI). Catchment similarity is expressed as the geometric distance in a three-dimensional Area–SAAR–BFI (ASB) space from the gauged catchment to the target catchment. The selected stations constitute a pooling-group (PG).

Figure 2 shows the geographical distribution and order of selection of the PG stations for a target ungauged catchment in the Pennines. The PG exercise is replicated for each of the four million ungauged catchments derived from the DTM, using an automated implementation of the FEH procedure; each PG includes 20 catchments selected from the gauged network.

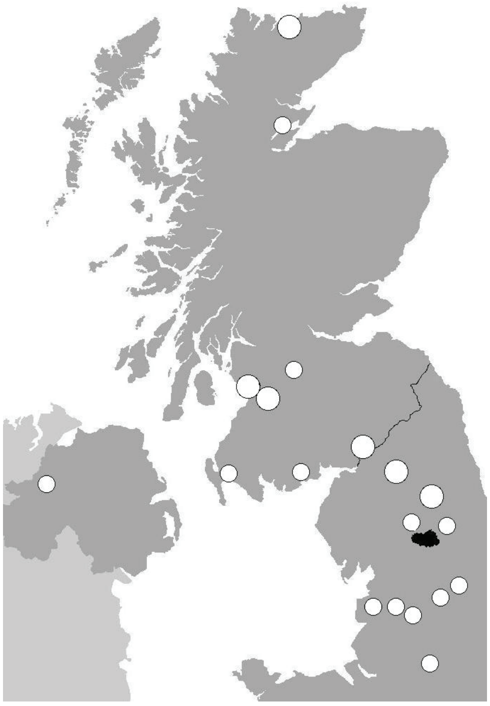


Fig. 2 Geographical distribution of the 19 gauging stations (white dots) from the pooling-group (100-year return period) of an ungauged site (solid black).

From the four million pooling-groups thus constituted, two sets of statistics are derived for each of the gauged catchments: number of inclusions (NI), i.e. the number of times a catchment is included in a PG; average score (AS) based on a catchment's average ranking position in the pooling-groups, ranging from 1 (always included last) to 20 (always first). The CUI synthesizes both into a single index, which ranges from 0 (lowest) to 100 (highest). Due to its construction, the CUI is not suitable for application across catchments of all sizes (Laizé *et al.*, 2006), and it is recommended that catchment appraisals are undertaken within a designated size range (see Case Study).

CATCHMENT SPATIAL ASSESSMENT

Typically, a comprehensive spatial assessment would begin by analysing individually the catchment descriptors and spatial data sets, then applying the RCI and CUI. The initial analysis identifies broad catchment types (e.g. lowland permeable, afforested upland), and gives an insight into how individual catchments relate to the gauged network and the country as a whole (e.g. to identify over- or under-gauged catchment types). This information is also necessary to guide the application of the RCI (e.g. selecting the reference area) and CUI (e.g. selecting the size range). In order to describe the reviewing procedure, this paper presents the assessment of a single gauged catchment associated with the Royal Windsor Park gauging station (39072) on the River Thames (Fig. 3).

Analysis of the catchment descriptors

Catchment 39072 has an area of 7125 km^2, an average annual rainfall of 690 mm, and a BFI of 0.66. According to the catchment size typology used in the European Water Framework Directive (WFD; European Commission, 2000), it is a large catchment (>1000 km^2). There are 101 gauged catchments of this type in the UK but only nine with an area >5000 km^2. Table 1 gives an indication of the density of the UK gauging network relative to the area descriptor. Catchment 39072 belongs to a type that is slightly less well gauged (higher ratio ungauged to gauged) in comparison to medium-sized catchments (100–1000 km^2). A similar picture emerges from the SAAR and BFI descriptors. It is therefore likely that 39072 belongs to an under-gauged catchment type. Indeed, within a distance of 0.5 point in ASB space (i.e. similar catchments), 39072 has only five neighbours; as a comparison, 80% of the gauged catchments have at least 12 other similar catchments, and the most well represented type has 71.

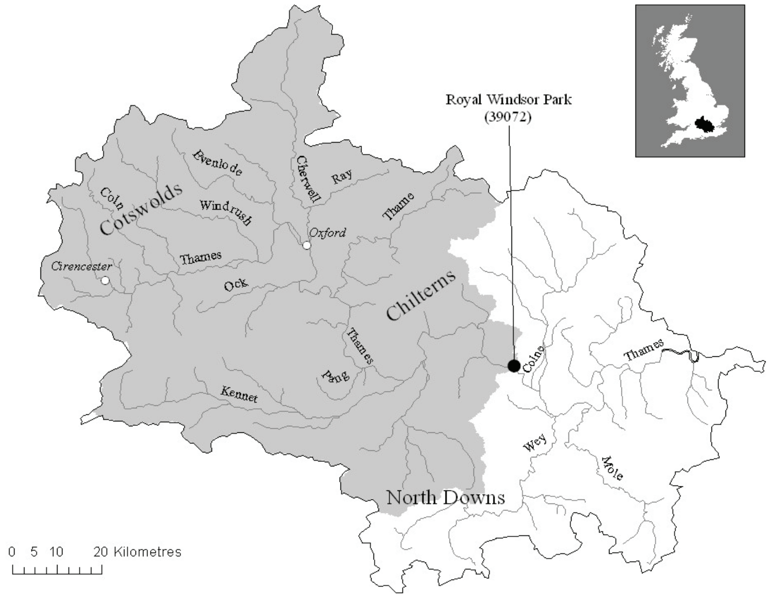


Fig. 3 Thames at Royal Windsor Park (39072); gauging station (black dot), catchment (grey area).

Table 1 Comparison of the number of UK gauged catchments with mainland Britain ungauged catchments relatively to their area; catchments larger than 0.5 km^2 only.

	Area (km^2) 0.5–10	10–100	100–1000	1000–10 000
Number of ungauged catchments	2 749 855	646 899	218 479	43 414
Number of gauged catchments	43	501	591	101
Ratio ungauged to gauged	63 950	1 291	370	430

Table 2 Land-use breakdown for catchment 39072 and England.

Land use category	Proportion (%) Catchment 39072	England
Sea/Unclassified	0.0	0.3
Woodland	13.2	11.0
Arable & horticulture	40.6	34.8
Grassland	34.0	38.1
Mountain, heath, bog	1.3	3.6
Built-up areas	10.4	11.2
Water (inland)	0.6	0.5
Coastal	0.0	0.5

Analysis of the spatial data sets

Elevation With more than 90% of its area below an elevation of 200 m, 39072 is a lowland catchment according to the WFD altitude typology; around a third of the gauged catchments in the UK are of that type.

Land use Catchment 39072 is very typical of England (Table 2). Considering the two main categories (Arable and Grassland), there are only around 35 lowland catchments with a similar mix of land use.

Hydrogeology The catchment hydrogeology comprises a mix of high permeability and very low permeability bedrock (about 40% each), which is typical of lowland England.

Application of the RCI

The initial assessments suggest that 39072 may be representative of UK lowlands, especially lowland England. This information guides the choice of reference areas to use in the RCI analysis. Following the procedure described earlier, the RCI for all UK gauged catchments were calculated using both England and lowland England (below 200 m) as reference areas. With an RCI of 48.3, 39072 is the 23rd most representative catchment for England in the entire gauged network. For lowland England, it is the 11th most representative catchment considering only the 101 gauged catchments with a size greater than 1000 km^2 (RCI = 51.8).

Application of the CUI

In this case study, catchment 39072 is included in nearly 4000 pooling-groups (Table 3), and has a high average rank within each PG. Correspondingly, 39072 has the second highest CUI for large catchments (>1000 km^2) across the UK. This confirms how influential this catchment is in relation to FEH applications, and, generally, to regionalization techniques.

Table 3 Ranked CUI for large catchments (>1000 km^2); first ten only (out of 101).

Station number	River	Area (km^2)	SAAR[a] (mm)	BFI[b]	NI[c]	AS[d]	CUI
15006	Tay	4586.8	1424	0.47	848	17.74	84.55
39072	Thames	7125.0	696	0.66	3862	16.49	79.18
15003	Tay	3211.0	1609	0.44	1486	16.70	77.27
28074	Soar	1300.9	641	0.41	5887	14.68	65.44
39002	Thames	3480.8	690	0.65	5452	14.47	63.28
39046	Thames	3425.7	691	0.65	5547	14.27	61.69
39130	Thames	4627.8	680	0.64	4894	14.32	61.52
43003	Avon	1455.1	807	0.89	2236	14.72	61.50
28093	Soar	1110.7	640	0.40	6016	13.48	55.41
43001	Avon	1616.5	809	0.88	2260	14.00	55.29

[a] Standard-period Average Annual Rainfall
[b] Base Flow Index
[c] Number of inclusions
[d] Average Score

DISCUSSION

The procedures presented in this paper are based solely on the physical characteristics of the gauged catchments. The procedures can be potentially applied to any of the four million catchments derived from the DTM, and to other countries where there is a GIS of key catchment descriptors. Although computationally demanding, the methodology could allow hydrometric network managers to identify the most influential ungauged catchments, and to explore the impact of adding stations to, or removing stations from the existing network.

In practice, it is expected that the catchment spatial indices will be used in combination with an appraisal of the time series (e.g. length of record), station hydrometric performance, artificial influences, and operational issues (e.g. logistics, maintenance costs) in order to provide measuring authorities with an objective assessment of the gauging station long-term strategic value. Using the indices, gauged catchments are assessed independently from their associated gauging station, so that network managers can particularly focus on sites where there are discrepancies between hydrometric capability and regional value (e.g. an unreliable station monitoring a very valuable catchment may be worth upgrading). The application of these indices to improve the overall cost-effectiveness of gauged network management is also investigated. Combined with information on flow regime characteristics and the hydrometric performance of gauging stations, catchment spatial indices constitute a powerful decision support mechanism to guide network evolution.

Acknowledgement This paper benefited from helpful discussion with colleagues. Some of the features in the figures are © NERC, and based upon © Crown Copyright 100017897 2005.

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