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Evaluating hydrometric networks for prediction in ungauged basins: a new methodology and its application to England and Wales

J. Hannaford, M. G. R. Holmes, C. L. R. Laizé, T. J. Marsh and A. R. Young

ABSTRACT

Flow estimates for ungauged catchments are often derived through regionalisation methods, which enable data transfer from a pool of hydrologically similar catchments with existing gauging stations (i.e., pooling-groups). This paper presents a methodology for indexing the utility of gauged catchments within widely used pooling-group methodologies for high and low flow estimation; this methodology is then used as the basis for a network evaluation strategy. The utility of monitoring stations is assessed using catchment properties and a parallel, but independent, appraisal of the quality of gauging station data, which considers hydrometric performance, anthropogenic disturbances and record length. Results from the application of the method to a national network of over 1,100 gauging stations in England and Wales are presented. First, the method is used to appraise the fitness for purpose of the network for regionalisation. The method is then used to identify gauges which monitor catchments with high potential for regionalisation, but which are deficient in terms of data quality – where upgrades in hydrometric performance would yield the greatest benefits. Finally, gauging stations with limited value for regionalisation, given the pooling-group criteria employed, are identified. Alongside a wider review of other uses of the network, this analysis could inform a judicious approach to network rationalisation.

Key words | floods, hydrometric network, hydrometry, low flows, monitoring, regionalisation

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INTRODUCTION

Hydrometric data provide the foundation for water management and underpin informed decision-making in areas such as water resources assessment, flood risk estimation, hydro-ecological management and hydropower generation. Around the world, however, hydrometric monitoring networks face increasing financial constraints and, in many countries, are declining (Vörösmarty 2002; Mishra & Coulibaly 2009). Under such circumstances, there is a growing need for improved network evaluation tools, to ensure that the potential of existing networks is maximised, within resource constraints. This means ensuring that resources are prioritised towards gauging stations that contribute most towards meeting the information needs of the user community, while also identifying those which are redundant. Network evaluation is often guided by economic and organisational considerations, but Marsh (2002) argues that strategic needs – for example, understanding hydrological processes, detecting climate-driven trends and developing regionalisation methods – should also be primary drivers of network evolution.

A significant body of research has been devoted towards developing network appraisal methods; a comprehensive review has recently been undertaken by Mishra & Coulibaly (2009). A majority of approaches are statistically based, employing regression analyses of streamflow parameters and physiographic properties of catchments (e.g., Moss & Tasker 1991), or assessing the information-transfer capability of a network (e.g., Yang & Burn 1994; Markus *et al.* 2003;

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Mishra & Coulibaly 2010). Other methods have focused on catchment characteristics: Laizé (2004), for example, developed a Representative Catchment Index for assessing the similarity of a gauged catchment to a reference area in terms of land cover and elevation characteristics.

One of the primary uses of hydrometric network data is for regionalisation, i.e., the prediction of hydrological characteristics at ungauged locations, via extrapolation in space from locations where gauged data are available. This is one of the key challenges in contemporary hydrology, and has been at the forefront of the Prediction in Ungauged Basins (PUB decade, 2003–2012) initiative (e.g., Franks *et al.* 2005). There are a wide range of mechanisms employed for regionalisation, which generally seek to transfer data from gauged to ungauged catchments via some measure of hydrological similarity. However, there is no widely agreed framework for catchment classification in hydrology (Wagener *et al.* 2007) and a proliferation of disparate indicators of hydrological similarity, and different catchment attributes, have been used in regionalisation studies (e.g., McIntyre *et al.* 2005; Yadav *et al.* 2007; Reichl *et al.* 2009). The concept of 'uniqueness of place' (Beven 2000) – whereby catchments are unique in terms of their topography, soils, rock types, vegetation and anthropogenic modification – arguably limits the potential for generalisation of regionalisation techniques. Attempts to set out a general catchment classification scheme, and appropriate metrics for judging similarity or dissimilarity, have been advanced by Wagener *et al.* (2007).

Despite the lack of any scientific consensus on a generalised approach to regionalisation, there are significant commonalities across many methods and, pragmatically, attempts have been made to adopt some national standards for regionalisation for particular purposes. Regionalisation methods often employ a Region of Influence (Burn 1990) approach, which enables prediction at ungauged locations through data transfer from pooling-groups of hydrologically similar catchments. In the UK, pooling-group methods are used for flood frequency estimation (the *Flood Estimation Handbook*, FEH; Institute of Hydrology 1999) and flow duration curve estimation ('Low Flows' software; Holmes *et al.* 2005). Previous authors have argued that network design strategies should ensure that streamflow/precipitation variability in space and time is sampled optimally, to facilitate estimation at ungauged sites (Mishra & Coulibaly 2009). While this aspiration is implicit in many statistical network evaluation methods, there is a good argument for using regionalisation methods as a starting point for network evaluation: the utility of regionalisation techniques largely depends on the number, spatial disposition and measurement capabilities of gauging stations in a hydrometric network. To this end, Laizé *et al.* (2008) developed a methodology for network appraisal for the UK based on techniques used within the FEH, to assess the utility of gauged catchments in terms of their capacity for supporting regionalisation.

The majority of published techniques for network evaluation have not addressed the quality of data provided by gauging stations. Data quality is an important concern for regionalisation studies, as estimates for ungauged sites, if based on poor quality gauged records, are likely to be subject to high degrees of uncertainty (Robson & Reed 1999). However, the reliability of river flow data is often compromised by the hydrometric inadequacies of gauging stations, especially at high and low flows (Marsh 2002; Herschy 2009). Additionally, for hydrological regionalisation studies, river flows must approximate a natural response to the physical properties of the catchment if meaningful relationships are to be derived (Gustard *et al.* 1992). Unfortunately, in a global context, a significant majority of river flow regimes are affected by human disturbances (Vörösmarty & Sahagian 2000) such as water withdrawals, effluent returns and storage in reservoirs.

This paper describes a new methodology which aims to address some of the gaps in previous network appraisal strategies. In particular, the approach assesses both the utility of a catchment and the quality of data produced by its associated gauging station. Building on the work of Laizé *et al.* (2008), the methodology developed herein quantifies the utility of gauging stations, and their associated catchments, primarily in terms of their utility in widely used regionalisation methods. It is therefore vital to consider the many other aspects of network utility (in particular, operational purposes such as abstraction licensing or flood warning) which are not encompassed in the methodology. The methodology was developed specifically to examine the strategic utility of the England and Wales (E & W) gauging station network, as part of a review commissioned by the Environment Agency (EA) for E & W (described in Davis *et al.* (2010)). The EA network review also considered the operational utility of gauging stations, and the strategic and operational reviews were given equal weight. The current paper focuses on the strategic component of the review, which has potential for application to other monitoring networks around the world. While the method has been developed and demonstrated in a rather data-rich environment, which may constrain certain aspects of its portability to data-sparse locations, it has the advantage of generic, modular structure; individual components may therefore find application elsewhere, according to data availability.

First, background is provided to the E & W streamflow monitoring network. The following section describes the new methodology, beginning with a general discussion of key concepts, and then the particular technical implementation of the method in E & W. The methodology is then demonstrated through its application on a national scale, to the EA's gauging station network in E & W, with particular emphasis on the applicability of the method for network rationalisation and prioritising future investment. Lastly, the utility of the new method is discussed – focusing on key advantages, limitations and transferability to other hydrometric networks – before conclusions are drawn.

THE ENGLAND AND WALES GAUGING STATION NETWORK

The UK gauging station network is very dense by international standards (Marsh 2002), which is largely a response to the diversity of the UK in terms of climate, geology, physiography, land use and patterns of water utilisation. While hydrometric network reviews have been carried out in Northern Ireland (Black *et al.* 1994) and Scotland (Copestake *et al.* 2006), no comprehensive network review of the E & W network has been undertaken previously. Sub-networks have been identified for the UK, such as the Benchmark Network of catchments for climate change monitoring (Bradford & Marsh 2003). Hitherto, however, detailed quantitative reviews have not been applied to the hydrometric network in its entirety.

The E & W network expanded rapidly in the 1960s and 1970s but, in recent years, growth of the network has slowed and, since 2005, has contracted slightly (see Figure 1). In common with many countries, the network faces resources constraints. Walker (2000) reviewed the economic value of the network, highlighting the difficulties in ascribing an economic value to the benefits accrued as a result of data from the network. A study undertaken by the National Audit Office (NAO 2005) identified that capital investment exceeds £250 million,

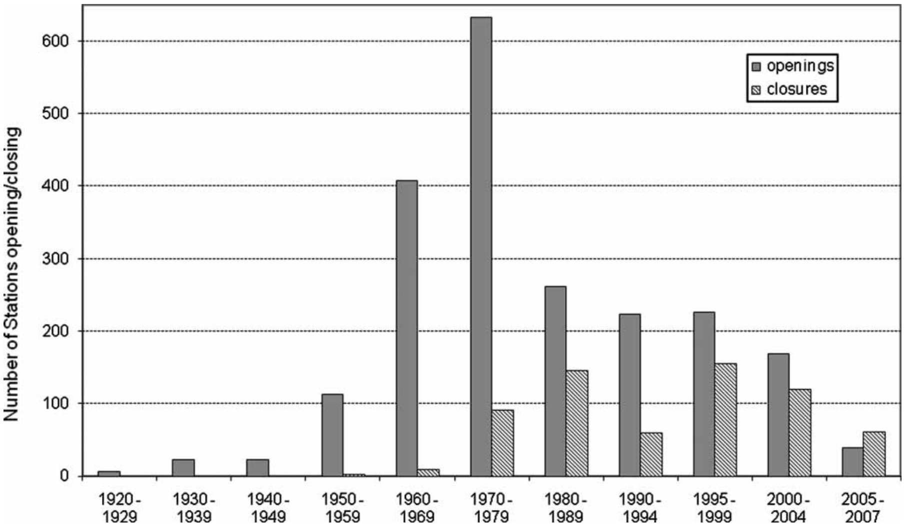

Figure 1 | Evolution of the England and Wales gauging station network. Number of gauging station openings and closures in decadal (1920–1989) and five-yearly (1990–present) time periods.

and annual running costs are £14 million. The study noted a 12% increase in the monitoring network over a 3-year period and recommended 'better control over the size of the network of monitoring sites'. This recommendation prompted the EA to carry out a hydrometric network review, including an assessment of the strategic utility of the network, for which the methodology produced in this paper was designed, along with a parallel appraisal of the operational importance of the network (Davis *et al.* 2010). At the time of the review (2008), there was a total of 1,393 active gauging stations currently in the network; in this paper, 1,116 sites were featured in the analysis, after excluding those sites for which data needed to calculate the various indicators used in the methodology were missing.

DESCRIPTION OF THE METHODOLOGY

Key principles

Much published work on network appraisal focuses on a relatively small number of stations (e.g., Black *et al.* 1994; Markus *et al.* 2003). A key specification of the new methodology was that it could be automated and applied rapidly to a national network of upwards of 1,000 gauging stations. Another important criterion for development was that the technique should be relatively simple and should deliver results that are easy to interpret, which favoured a scoring system based on catchment and station attributes rather than the overtly statistical approach favoured by many previous studies; as discussed in the introduction, many methods rely on concepts such as information theory (e.g., Yang & Burn 1994; Markus *et al.* 2003; Mishra & Coulibaly 2010) which are less readily interpretable by non-specialists. Specifically, the network evaluation objectives that the methodology was designed to address are as follows:

- Assess the current fitness for purpose of a network for servicing regionalisation.
- Identify where improvements in data utility would yield the greatest benefits for regionalisation methods.
- Identify redundant stations, which are of low value for regionalisation and could (in principle) be decommissioned without any deleterious impact on regionalisation.
- Identify a core network of the highest utility gauging stations.

The latter objective is the subject of ongoing research, and is beyond the scope of the present paper, although brief consideration is given to the issue in the discussion. The methodology is designed to allow separate appraisals of the utility of a gauged catchment for regionalisation, and the quality of the data produced by the gauging station itself. A key concept is that the catchment utility can be quantified *independently* of the gauging station which monitors it. The potential of a catchment for regionalisation is a function of its physical characteristics (e.g., area, wetness, soils); whether this potential can be realised, however, is contingent on the gauging station. Underlying the mechanism, therefore, is a conceptual scoring scheme which quantifies the following attributes of a catchment and its associated gauging station:

- The catchment's 'Potential Benefit' (PB): this indicates the theoretical utility of the gauged catchment for use in regionalisation.
- This potential is then constrained by the 'Actual Performance' (AP) of the gauging station, i.e., the quality of the data provided by the station.
- Overall, these are combined to yield a 'Realised Benefit' (RB) according to a simple equation:

$$\begin{aligned}\text{Realised Benefit (RB)} &= \text{Potential Benefit (PB)} \\ &\quad \times \text{Actual Performance (AP)}\end{aligned} \tag{1}$$

High and low flow estimation approaches typically employ different techniques, and many gauging stations are better suited to either high flow measurement or low flow measurement (Marsh 2002). The methodology is designed, therefore, to assess the utility of stations for high and low flow estimation separately. The two components can be combined to give an overall score for gauging station utility. The overall structure of the methodology is summarised in Figure 2, which also provides a framework for the following discussion of the implementation of the method in E & W.

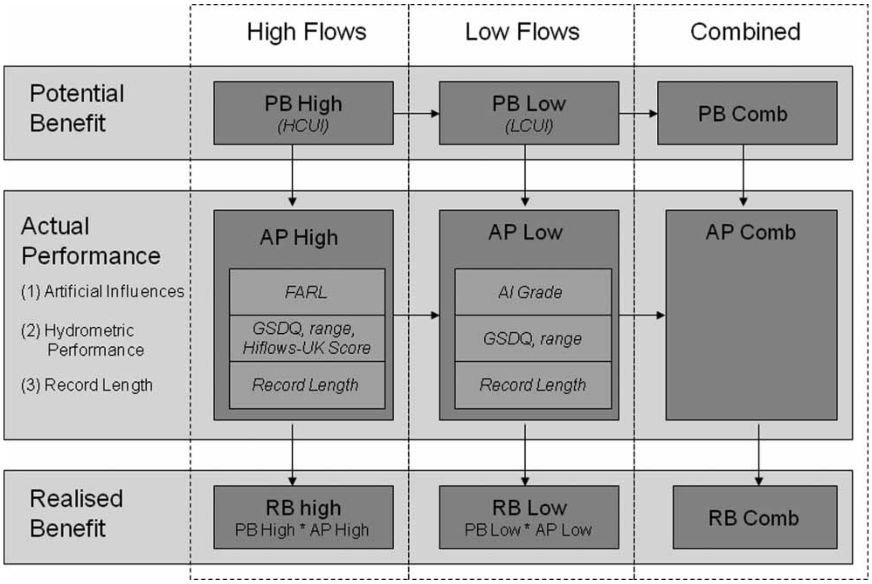

Figure 2 | Schematic overview of methodology.

Catchment utility – potential benefit

Many hydrological regionalisation methods are based on the identification of pooling-groups of hydrologically similar 'donor' gauged catchments which are then used to estimate flows at a 'target' ungauged site, donors being selected on the basis of having similar catchment characteristics to the target. In the new methodology, the pooling-group concept is exploited to assess the value of gauging stations in a hydrometric network. A gauged catchment which is commonly called into pooling-groups, and/or which has a high weight within them, can be thought of as having high value compared with one which is infrequently called and/or has low weight. Within the new methodology, therefore, UK national standard techniques for high and low flow estimation, both of which are based on the pooling-group concept, were used as a means of assessing the utility of catchments for regionalisation.

Within the UK, the national standard for flood estimation is the FEH. Laizé *et al.* (2008) developed a Catchment Utility Index (CUI) for assessing the potential of gauged catchments for flood estimation, by quantifying their utility for populating FEH pooling-groups for ungauged catchments. In the FEH (and therefore, by design, the CUI) pooling-groups are determined by an index of catchment similarity based on three catchment descriptors: size (catchment area), soils (Base Flow Index estimate from Hydrology of Soil Types, BFIHOST; Boorman *et al.* 1995) and wetness (Standard Average Annual Rainfall, 1961–1990). These are derived using gridded spatial datasets based on the Integrated Hydrological Digital Terrain Model (IHDTM, Morris & Flavin 1990). The IHDTM was designed to be consistent with the UK drainage network and allows the boundaries of around four million surface water catchments to be derived (this discrete number of catchments is a construct due to the resolution of the IHDTM; along a drainage path, catchment outlets are 50 m apart in the east–west and/or the north–south direction). Figure 3 illustrates the FEH pooling-group concept for a single ungauged site in the UK.

The CUI was thus used to assess the PB of gauging stations in the E & W network. The target catchments were all four million catchments that can be derived from the UK IHDTM, so four million pooling-groups (analogous to the example presented in Figure 3) were created. From these, the relative rankings and weights of gauged catchments were derived using the CUI methodology as described by Laizé *et al.* (2008), but herein referred to as a High Flows Catchment Utility Index (HCUI). While the donor gauged catchments are from E & W only,

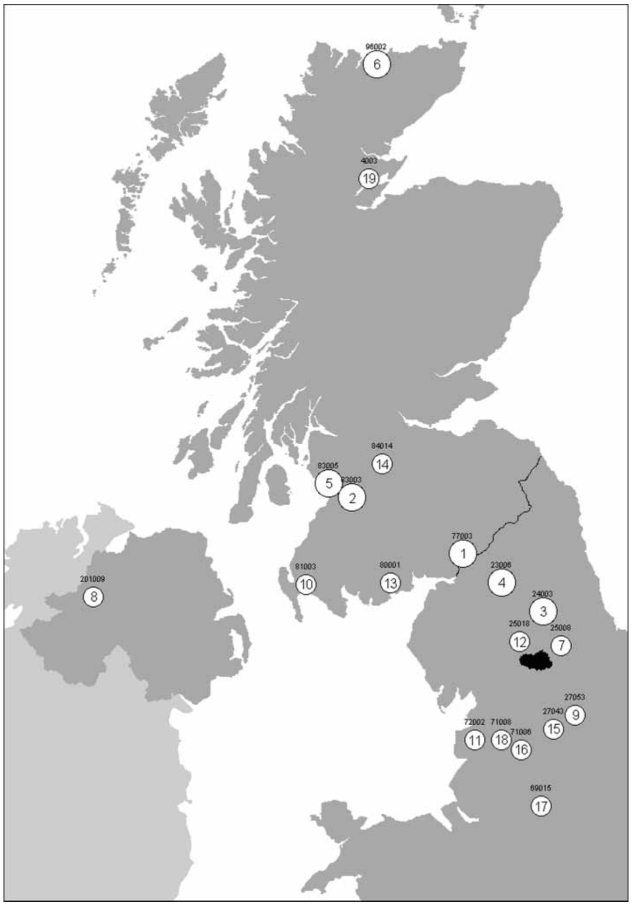

Figure 3 | Example of a *Flood Estimation Handbook* pooling-group for a catchment in upland England (coloured in black), showing pooling-group members and their relative weights (size of circles and rank contained within circles) within the group. Reproduced from Laizé *et al.* (2008).

pooling-groups were also derived for ungauged target catchments from across the whole of the UK because, in practice, E & W catchments are also used to populate pooling-groups for ungauged locations in Scotland and Northern Ireland. The HCUI method thus applied yielded a score for all 1,116 donor gauging stations in the network based on their frequency of occurrence and relative ranking within the four million pooling-groups. No adjustment was made to remove urban catchments from pooling-groups, as carried out in the FEH in practice; urban catchments can have considerable strategic value (see Discussion).

For low flows, the national standard for flow estimation in ungauged sites is the Low Flows 2000 methodology (Holmes *et al.* 2005). Hydrological similarity is based on the hydrogeological setting of target and donor catchments. Pooling-groups are constructed using the fractional extent of Hydrology of Soil Types (HOST) classes (Boorman *et al.* 1995), using a Region of Influence methodology described in Holmes *et al.* (2002). The target catchments were a set of 5,000 ungauged catchments from across E & W, used for the EA's 'Initial Characterisation of Waterbodies' carried out to meet the obligations of the Water Framework Directive (UKTAG 2010). These catchments are broadly representative of the hydrogeology of E & W. The frequency with which gauged catchments are called and their relative ranking within pooling-groups was then derived from the 5,000 pooling-groups assembled for these catchments using the Region of Influence method (Holmes *et al.* 2002) These were then combined into a Low Flows Catchment Utility Index (LCUI), analogous to the HCUI for high flows but employing a different combination algorithm as described by Hannaford *et al.* (2008).

HCUI and LCUI scores were translated into categorical PB scores as follows: the HCUI and LCUI results were divided into quartiles, giving four classes of PB, the first quartile scoring 100 (PB100), second quartile scoring 75 (PB75), etc. The results of this analysis are presented in Figure 4, which shows that there is a reasonable spread of the PB classes over the E & W network, although there is some clustering which reflects the spatial distribution of catchment properties. This clustering is not an obstacle to the application of the techniques, as catchments are judged on importance for pooling, irrespective of geographical location.

Data utility – actual performance

The quality of streamflow data is affected by many factors, which will have different degrees of importance from one network to another. The following three generic factors were considered to be important in E & W, and are likely to be of relevance to most national hydrometric networks: artificial influences (AIs), hydrometric performance and length of record. The following sections discuss the techniques used to quantify the impact of these factors, and a methodology for combining them.

Artificial influences

An existing numerical indicator of reservoir and lake influences at high flows, available for the UK, is the Flood

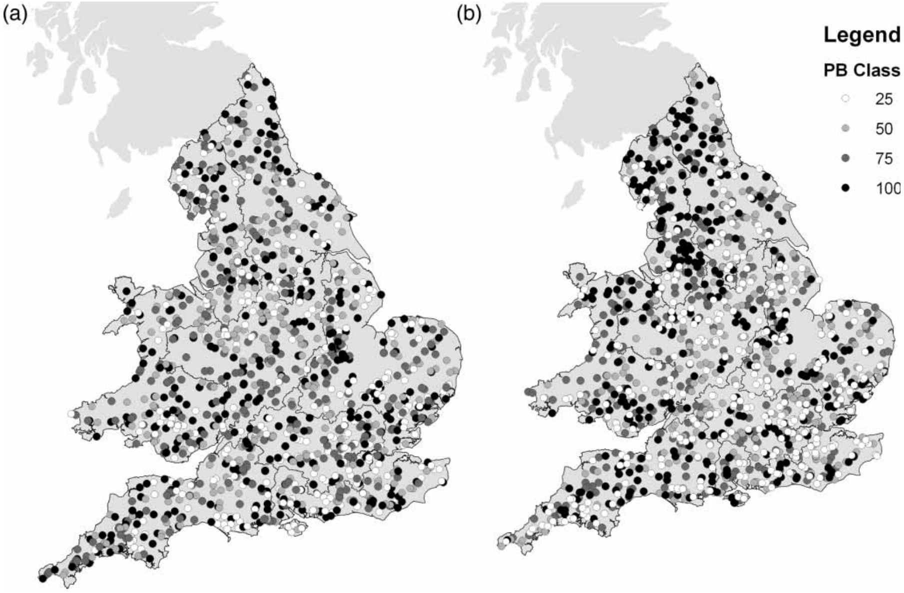

Figure 4 | Distribution of Potential Benefit (PB) scores for 1,116 catchments (circles shown at catchment outlets) across England and Wales, for (a) high flows, (b) low flows.

Attenuation due to Reservoirs and Lakes (FARL) index (Bayliss 1999). FARL is used within the FEH to determine suitability of catchments for inclusion in pooling-groups. It characterises the attenuation of floods due to standing waterbodies, based on the sub-catchment area affected by on-line reservoirs/lakes relative to the whole catchment area (for further details see Bayliss (1999)). FARL takes values from 0 to 1, with $1 =$ no impounding reservoirs or lakes present; sites downstream of reservoirs can have FARL values below 0.7.

For low flows, a quantitative assessment of the degree of anthropogenic disturbances on the flow regime was required. To facilitate this, the Low Flows 2000 model for estimating natural and influenced flows (Holmes *et al.* 2005) was populated with influence data (e.g., licensed abstraction rates, discharge consents and reservoir release profiles) at locations in the catchments of gauging stations, using the process described in Holmes *et al.* (2005). The influence data were those used in the EA's 'Initial Characterisation of Waterbodies' project (UKTAG 2010). The model provided, for various flow thresholds, estimates of natural flow and estimates of influenced flow (affected by abstractions, discharges and reservoirs), from which it is possible to calculate the net degree of impact from all influences for a given threshold. The net degree of influence at Q95 (IMP_{net}) and the individual influences (IMP_{ind} for abstraction, discharges and impoundments) were then combined into a scoring scheme (Table 1), with stations assigned to various classes (each carrying a numeric score) according to the degree of impact. The individual impacts are included as they may have large flow regime effects, even if net impact is low (e.g., due to large abstractions and discharges cancelling each other out). The results of this analysis are presented in Figure 5. As would be expected, impacted sites tend to cluster in the populated areas of England,

Table 1 | Classification and scoring scheme used for assessment of artificial influences at Q95

Net impact (IMP_{NET})	Individual impact (IMP_{IND})	AI class	Score
No influences present			100
<10%	<10%	1	90
<10%	>10% and <30%	2	80
<10%	>30%	4	60
>10% and <20%	<10%		
>10% and <20%	>10% and <30%	3	70
>10% and <20%	>30%	5	50
>20%	<10%		
>20%	>10% and <30%	6	30
>20%	>30% and <50%	7	20
>20%	>50%	8	10

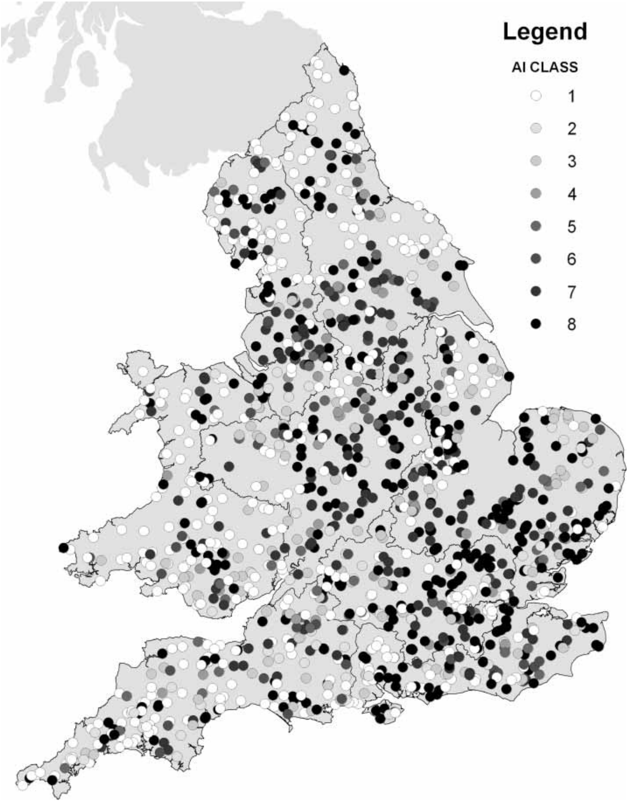

Figure 5 | Distribution of artificial influence (AI) scores for low flows for all catchments in E & W (circles shown at catchment outlets).

while the majority of natural sites are in the more remote upland areas of the west.

Hydrometric performance

Three approaches were used to assess hydrometric performance. First, Gauging Station Data Quality classifications (GSDQs; Lamb *et al.* 2003) were employed. The GSDQ uses a range of metrics which reflect various aspects of performance and data quality, including generic factors such as the significance of missing data and accuracy of level measurement and other more specific issues relevant to high (e.g., unmeasured bypass flow, number of gaugings in the high flow range) or low flows (e.g., sensitivity at Q95, weed growth management). Based on the mechanisms described by Lamb *et al.* (2003), for any one site these scores are aggregated into overall scores of Good, Caution or Poor for high and low flows separately. GSDQs were only available at around 40% of sites; where these were absent, a second approach was taken: a 1–5 scoring scheme was applied, based on expert judgement of regional hydrometric personnel. A third approach to indexing data quality, for high flows only, was an indicator of suitability for use in pooling-groups (Hiflows-UK 2010), which classifies whether sites are suitable for pooling, or only suitable for estimating the median annual flood, or are suitable for neither. This score was available for 72% of sites in the network.

From these various indicators, an overall Hydrometric Data Quality (HDQ) score was derived. For low flows, the HDQ score used the GSDQ where available; alternatively, the subjective score based on expert judgement was used. For high flows, 50% of the HDQ score was applied in the same way, and 50% was based on the Hiflows-UK classification (effectively, Hiflows-UK sites are awarded a bonus score for their previously defined utility in flood estimation).

Record length

Record length (RL) is influential upon regionalisation as it affects the extent to which a gauging station record captures historical variability (e.g., Hue *et al.* 2005). Longer records are more valuable as they are likely to capture a wider range of extreme flood/low flow events, which enhances transferability of flood frequency curves or flow duration curves to ungauged sites. As such, record length is an explicit factor affecting weighting in pooling-groups in the FEH (the method recommends a minimum record length of 7 years for pooling; Institute of Hydrology 1999). Furthermore, long time series are of pivotal importance for other strategic goals such as trend detection: Kundzewicz & Robson (2000) recommend 50 years as a minimum length of record for non-stationarity tests. Record length is a particularly important factor in E & W since, with most network expansion occurring in the 1960s to 1970s, there are comparatively few long records (see Figure 2).

An overall data utility (Actual Performance) score

The three components AI, HDQ and RL were combined into an AP score, which is used to classify the quality of data being produced by a gauging station. Some indicators (e.g., low flows, AIs) were already based on a categorical scheme, but for others a categorical score was applied, with scores assigned to each category, e.g., for record length: <5 years = 10%; 6–10 years = 40%; 11–20 years = 60%; 21–35 years = 70%; 36–50 years = 80%; >50 years = 100%.

The categorical scores were then combined with a weighting scheme. Weightings were based on specifications dictated by perceived importance of the components, as assessed by stakeholders in the network review. AP is assessed as follows:

$$\mathrm{AP} = \frac{a\mathrm{HDQ} + b\mathrm{AI} + c\mathrm{RL}}{a + b + c} \qquad (2)$$

where: AP = Actual Performance score; HDQ = Hydrometric Data Quality; AI = Artificial Influences; RL = Record Length; a, b, c = weights.

For low flows, the weights used for scoring were:

$a = 35\%$, $b = 35\%$, $c = 30\%$.

For high flows, the weights used were:

$a = 40\%$, $b = 30\%$, $c = 30\%$.

The increased importance of HDQ for high flows reflects the fact that AIs on the high flow regime are less prevalent (the influence of reservoirs is comparatively low by international standards) whereas hydrometric issues such as gauge bypassing, drowning of structures or uncertainty in high flow ratings are perceived to be a fundamental issue in high flow estimation in the UK (e.g., Marsh 2002).

Equation (2) yielded an AP score, which was used to enable calculation of RB when combined with PB (Equation (1)). Clearly, different weightings would have different effects on rankings. These scores are only indicative, and used for ranking and grouping gauging stations – the key principle is that the AP score can be used as a rapid, first-pass screening tool, whereas more penetrating assessments can then be made by examining the individual HDQ, AI and RL factors.

RESULTS FROM APPLICATION TO THE ENGLAND AND WALES NETWORK

This section presents the results of the case study application to E & W. The first application of the method is to assess the overall fitness for purpose of the E & W network. In light of this analysis, the capacity of the method for guiding network evolution is demonstrated, first as applied to improving the hydrometric performance of key gauging stations and second in relation to network rationalisation.

Fitness for purpose of network for regionalisation

From the point of view of maximising resources, it is desirable to have a network which is fit for purpose. In regionalisation terms, this means that high potential catchments (those frequently called into pooling-groups, and/or which carry high weight within them) should have good quality monitoring capability to deliver their PBs. The methodology is well placed to assess fitness for purpose, by quantifying how many catchments in the highest PB classes have gauging stations that provide data which are suitable for pooling, given some pre-defined criteria defining minimum acceptable levels of AI, HDQ and RL for pooling. For high flows, the criteria were: (following standard criteria of the FEH) FARL index of >0.9; minimum record length of 7 years; and, for data quality, a 'suitable for pooling' flag according to Hiflows-UK or, for non-Hiflows-UK sites, GSDQ scores of Good or Fair. For low flows: (following standard Low Flows 2000 criteria) AI CLASS <3; minimum record length of 6 years; and for data quality, GSDQ score of Good or Fair.

The above criteria were applied and the number of sites which met the criteria was computed for each PB class (Table 2). Overall, around 50% of the network is suitable

Table 2 | Suitability for pooling (according to criteria listed in the sub-section on 'fitness for purpose') across the four Potential Benefit categories, for both high flows and low flows

	Total number of sites	Number suitable for pooling	% suitable
High flows			
PB100	268	116	43.28
PB75	287	137	47.74
PB50	283	136	48.06
PB25	278	138	49.64
Low flows			
PB100	279	78	27.96
PB75	276	64	23.19
PB50	285	72	25.26
PB25	276	80	28.99

for high flows pooling. For low flows, only 30% of sites meet the criteria. This is principally due to the strict criteria for low flows regionalisation, which tolerates only minimal degrees of AI on Q95, and the pervasive impact of AIs across much of E & W, as shown in Figure 5 and highlighted by previous authors (Marsh 2002). For both high and low flows, the proportion of sites suitable for pooling is broadly similar across the PB categories (Table 2). A large proportion (>40%) of catchments with the highest potential have gauging stations which are currently failing to deliver. This suggests that an overall improvement in regionalisation could be achieved within existing resources by increased investment in some high potential catchments, at the expense of some low potential catchments which could be downgraded (or possibly decommissioned; see below). An additional catalyst for improving the failing high potential sites is the frequency with which these sites are called into pooling-groups, and their high weightings, which implies that they may have a deleterious effect on pooled flow regime estimates. There are, therefore, scientific benefits to be gained from improving high potential sites which are currently inadequate in terms of their hydrometric performance.

Identifying priority gauging stations for improvement

The scope for improving the utility of stations' gauging catchments which are heavily affected by human influences is somewhat limited. Attempts can be made to adjust flows to account for easily quantified AIs through flow naturalisation, but this requires a good knowledge of influences, and the uncertainty in naturalised estimates is an obstacle to their wider use. In practice, flow naturalisation is only carried out routinely for a small number of E & W gauging stations (Marsh & Hannaford 2008), although the number is increasing. In contrast, there is considerable potential for enhancing hydrometric performance through improved measurement practices, and the logical priority for such investment would be those catchments with high PB and limited degrees of AIs.

An analysis was conducted to examine the numbers of sites in the E & W network which are unsuitable for pooling due to being artificially influenced, relative to those which are unsuitable due to poor hydrometric quality. Table 3 assesses the number of sites which are relatively natural (for low flows, AI CLASS <5 was applied; this was more tolerant than the analysis applied in the previous section, in order to include a higher number of stations). Table 3 demonstrates that AIs are a predominant factor in low flows with almost half of the highest PB catchments being unsuitable due to heavily influenced regimes. Of the 146 remaining highest potential catchments which are relatively natural, 22% are unsuitable due to having gauging stations with poor hydrometric performance. For high flows, Table 3 demonstrates that AIs are less important, with fewer catchments rendered unsuitable in terms of FARL, but hydrometric limitations are the main limiting factor.

Table 3 | Proportion of stations suitable for hydrometric improvement, across the four Potential Benefit categories, for high and low flows. Based on number of sites which are relatively natural but with inadequate hydrometric data quality (HDQ)

	Total number of sites	Number of 'natural' sites (AI CLASS <5)	Number of 'natural' sites failing due to HDQ	% of 'natural' sites failing due to HDQ
High flows				
PB100	268	237	106	45.3
PB75	287	267	115	44.7
PB50	283	261	104	38.8
PB25	278	263	103	39.0
Low flows				
PB100	279	146	31	21.7
PB75	276	136	31	19.2
PB50	285	154	24	14.3
PB25	276	137	15	9.9

Screening all highest potential sites for those stations with acceptable AIs but poor HDQ enables priority candidates for improvement to be identified. These can then be reviewed to assess the feasibility (and likely costs) of overcoming current hydrometric limitations. Realistically, improvements in hydrometric performance may not be feasible in some settings, particularly where stations are subject to chronic problems – for example, a measuring structure which is insensitive at low flows may be extremely costly to replace or upgrade. In many cases, however, additional investment of resources may improve reliable flow measurement, thereby realising the potential of key sites. Mishra & Coulibaly (2009) discuss the potential of recent developments in streamflow measurement for network improvement, including new methods such as Acoustic Doppler Current Profilers (ADCPs), which enable measurements to be carried out at a lower cost in environments which would previously have been very challenging.

As an example of the application of the methodology to identify candidates for improvement, Table 4 lists stations in one hydrometric region (Wales) which fall into the highest potential (PB100) category for high flow estimation. Stations in the top half of the table have AP values below the median for E & W as a whole. Of these stations, some are constrained by both poor hydrometric performance and high FARL values (e.g., stations 55032 and 67019), and there would therefore be limited value (in regionalisation terms) of improving flow measurement. AP scores for other sites (e.g., 66012 and 67027) are affected by comparatively short records; for these sites, performance scores will improve in future reviews. The principal candidates for improvement are those stations which have long records, are unimpacted by reservoir effects, but which currently produce poor quality data. For example, 66006 is hampered by unmeasured flow

Table 4 | Selected metadata and scores for sites in Wales with high Potential Benefit (PB100) for estimation of high flows, ranked in order of Actual Performance for high flows (AP high). Sites above bold line have AP high values below the median (for E & W as a whole)

Station number	**Station name**	**Record length**	**Record length score**	**Hiflows pooling**	**HDQ high**	**FARL**	**FARL score**	**AP high**	**PB high**	**RB high**
55032	CABAN(Dam)	27	70		10	0.763	20	29	100	29
65001	BEDDGELERT	46	80	QMED	10	0.896	20	42	100	42
67019	WEIR X	11	60	QMED	60	0.851	20	46	100	46
66012	PONT CAETHIN	12	60		60	0.979	60	48	100	48
57015	MERTHYR TYDFIL	29	70	POOLING	10	0.85	20	49	100	49
65014	HAFOD WYDR	13	60		40	0.981	80	50	100	50
55023	REDBROOK	38	80	QMED	10	0.979	60	54	100	54
67027	IRONBRIDGE US	14	60		100	0.956	60	56	100	56
67033	CHESTER SB	14	60		100	0.959	60	56	100	56
66006	PONT Y GWYDDEL	34	70	QMED	10	0.98	80	57	100	57
66003	BRYN ALED	37	80	NEITHER	80	0.95	60	58	100	58
56019	ABERBEEG	24	70	NEITHER	100	0.957	60	59	100	59
58010	ESGAIR CARNAU	32	70	QMED	10	1	100	63	100	63
66011	CWMLANERCH	44	80	QMED	60	0.976	60	64	100	64
57005	PONTYPRIDD	37	80	POOLING	60	0.949	40	68	100	68
55013	TITLEY MILL	41	80	POOLING	10	0.999	80	70	100	70
59001	YNYSTANGLWS	50	80	POOLING	10	0.996	80	70	100	70
66004	BODFARI	38	80	QMED	100	0.975	60	72	100	72
56001	CHAINBRIDGE	51	100	POOLING	10	0.98	80	76	100	76
58002	RESOLVEN	33	70	POOLING	60	0.983	80	77	100	77
66005	RUTHIN WEIR	31	70	POOLING	60	0.995	80	77	100	77
57006	TREHAFOD	37	80	POOLING	60	0.986	80	80	100	80
63001	PONT LLOLWYN	44	80	POOLING	100	0.99	80	88	100	88
67008	PONT Y CAPEL	43	80	POOLING	100	0.99	80	88	100	88
67005	BRYNKINALT WEIR	51	100	POOLING	100	1	100	100	100	100

bypassing the station (Marsh & Hannaford 2008), but otherwise performs well at high flows. If bypassing flow could be captured through ADCP measurements, the site could achieve its potential. Station 55023 has a very long record and is a large, representative catchment of high national importance. However, the stage–discharge relationship is not confirmed at the highest flows, which limits its value for pooling; improvements in the rating curve would yield an increase in the RBs in this station.

Network rationalisation

Network rationalisation is a necessary response to resource limitations, but it is important that any decrease in the size of the network does not affect its utility. The methodology presented in this paper can be employed to support judicious network rationalisation, through application as a screening tool, to identify stations which are contributing little to regionalisation – those with lowest PB, which are also failing to deliver in terms of data quality, and are thus not realising their benefits (i.e., have low RB scores).

As an example of an application to the E & W network, high and low flow scores can be combined to screen for those stations which are of limited utility for both objectives. Of the 1,116 catchments studied, 67 are in the lowest PB quartile (PB25) for both high and low flows. Critically, however, stations of limited PB, but with good AP, should not necessarily be considered redundant. While the catchment characteristics of low potential sites may render them of limited utility in pooling, there are many other factors to consider (see Discussion), so stations producing good quality data may be of strategic benefit through their data utility alone. Thus, those of the 67 candidate sites with a combined AP higher than the median of the candidates (63.25) were not considered further, leaving 34 stations, as presented in Table 5. This is an illustrative exercise, yielding a small number of sites (<2% of the network). It should be noted that the sites in Table 5 are purely candidates for review based on the application of this methodology, and will not correspond to the candidates identified in the EA Network Review (Davis *et al.* 2010), which also considered operational benefits in parallel.

Table 5 shows the characteristics of the lowest scoring candidates, demonstrating that the low RB is associated with a combination of high AIs, short records, and poor hydrometric quality at either high or low flows (or both). This low level of RB suggests that decommissioning these sites would not be a significant loss to the network, in terms of regionalisation.

While the method can be used to identify candidates for decommissioning, there remains a need to review all candidates in detail, with additional judgement needed to reinforce decisions on station decommissioning. First, stations may be important for other scientific goals. For example, 39056 (Catford) has low PB, but is a highly urbanised catchment. While the FEH employs only rural catchments for pooling, heavily urbanised catchments are important for advancing process understanding and improving predictive capability in built-up areas (Kjeldsen 2010), but are comparatively rare in E & W. High flow measurement is often challenging in responsive urban catchments, so with good high flows performance this site could be considered strategically important for this application. Second, and most importantly, operational considerations may outweigh strategic considerations. For example, the catchment 27021 has limited utility for regionalisation, but is very densely populated, covering large parts of the conurbation of South Yorkshire, and has a very long record; it is therefore of very high value for flood warning and water resources management.

DISCUSSION

In terms of applicability, the method presented in this paper has several distinct advantages. It can be automated and applied rapidly, as a screening tool to guide network evaluation, and is interpretable through simple but defensible scoring techniques: the concepts of PB, AP and RBs are transparent and translate into clear messages for network managers. The modular approach means that stations can be judged for particular purposes, relevant for different sectors of the user community, as well as for their overall performance.

The key emphasis on regionalisation provides a scientific foundation to the method, and also ensures the method is designed to meet the specific needs of a wide community of users. The focus on national-standard pooling-group

Table 5 | Low value sites for regionalisation – sites with lowest PB for both high and low flows, ranked in order of combined Realised Benefit, showing selected metadata and components of AP score

Station number[a]	Name	Record length	Record length score	HDQ high	HDQ low	AI class	AI score	FARL	FARL score	AP high	AP low	RB high	RB low	AP combined	RB combined
U33095	MILTON KEYNES M1	0	10	100	10	7	10	0.923	40	35.0	10.0	8.8	2.5	22.5	5.6
U32001	SOUTH BRIDGE	0	10	80	10	4	10	0.953	60	37.0	10.0	9.3	2.5	23.5	5.9
F1706	LEEDS CITY STN	5	10	60	10	6	30	0.968	60	33.0	17.0	8.3	4.3	25.0	6.3
37051	NORTH WYCKE	7	40	100	10	8	10	0.989	80	56.0	19.0	14.0	4.8	37.5	9.4
39078	FARNHAM	30	70	10	10	8	10	0.984	80	47.0	28.0	11.8	7.0	37.5	9.4
33067	BURWELL	26	70	10	10	7	20	0.988	80	47.0	31.5	11.8	7.9	39.3	9.8
654602005	LITTLEBOURNE GS	5	10	100	80	8	10	0.988	80	47.0	34.5	11.8	8.6	40.8	10.2
40018	LULLINGSTONE	39	80	60	10	8	10	0.906	40	58.0	31.0	14.5	7.8	44.5	11.1
33052	SWAFFHAM BULLBK	45	80	10	10	8	10	0.998	80	60.0	31.0	15.0	7.8	45.5	11.4
27076	THORNTON LOCK	26	70	10	60	8	10	0.98	80	47.0	45.5	11.8	11.4	46.3	11.6
39056	CATFORD	30	70	10	10	8	10	0.99	80	67.0	28.0	16.8	7.0	47.5	11.9
39143	BOURTON OTW	12	60	10	100	6	30	0.942	40	32.0	63.5	8.0	15.9	47.8	11.9
444220	DEWLISH VILLAGE	10	40	60	100	8	10	0.994	80	48.0	50.5	12.0	12.6	49.3	12.3
28083	DARLASTON US	25	70	80	80	8	10	0.942	40	49.0	52.5	12.3	13.1	50.8	12.7
33081	EXNING	13	60	10	100	8	10	1	100	50.0	56.5	12.5	14.1	53.3	13.3
33073	FULBOURN	16	60	10	100	8	10	1	100	50.0	56.5	12.5	14.1	53.3	13.3
35010	BRAMFORD	39	80	10	100	8	10	0.961	60	44.0	62.5	11.0	15.6	53.3	13.3
39015	LODGE FARM	33	70	60	60	8	10	1	100	63.0	45.5	15.8	11.4	54.3	13.6
28047	BLYTH	37	80	60	80	8	10	0.956	60	54.0	55.5	13.5	13.9	54.8	13.7
39074	SHEEPPEN BRIDGE	28	70	60	100	8	10	0.975	60	51.0	59.5	12.8	14.9	55.3	13.8
40015	FAIRBROOK FARM	38	80	60	60	7	20	0.999	80	60.0	52.0	15.0	13.0	56.0	14.0
31013	IRNHAM	39	80	10	100	8	10	0.997	80	50.0	62.5	12.5	15.6	56.3	14.1
39127	LITTLE MISSENDEN	14	60	100	100	8	10	0.961	60	56.0	56.5	14.0	14.1	56.3	14.1
751006	NEWLANDS BECK	3	10	100	100	1	90	0.999	80	47.0	69.5	11.8	17.4	58.3	14.6
29008	MARKET RASEN	8	40	10	100	1	90	0.991	80	38.0	78.5	9.5	19.6	58.3	14.6
444110	SOUTH HOUSE	16	60	60	100	8	10	1	100	60.0	56.5	15.0	14.1	58.3	14.6

(*continued*)

Table 5 | continued

Station number[a]	Name	Record length	Record length score	HDQ high	HDQ low	AI class	AI score	FARL	FARL score	AP high	AP low	RB high	RB low	AP combined	RB combined
41003	SHERMAN BRIDGE	49	80	10	100	8	10	0.978	60	54.0	62.5	13.5	15.6	58.3	14.6
28014	MILFORD	48	80	80	80	7	20	0.96	60	58.0	59.0	14.5	14.8	58.5	14.6
33015	WILLEN	46	80	100	60	7	20	0.93	40	66.0	52.0	16.5	13.0	59.0	14.8
510580	AVILLE FARM	3	10	80	100	1	100	1	100	49.0	73.0	12.3	18.3	61.0	15.3
730120	BOWSTON	8	40	100	100	1	90	0.948	40	44.0	78.5	11.0	19.6	61.3	15.3
27021	DONCASTER	49	80	10	100	7	20	0.922	40	58.0	66.0	14.5	16.5	62.0	15.5
335	ABBEY BRIDGE	16	60	60	60	1	90	0.998	80	54.0	70.5	13.5	17.6	62.3	15.6

[a] This column shows the full station number for sites on the UK National River Flow Archive (NRFA) (as published in Marsh & Hannaford (2008), which are highlighted in bold). For Environment Agency sites not on the NRFA, the local numbering system is used.

methods means the recommendations resonate with hydrologists, engineers and network managers alike. Furthermore, if national standards change, the same principles can be applied using new pooling-group mechanisms. (Since the application of this method to E & W, new developments have been made to the FEH methodology (Kjeldsen & Jones 2009), which can be accommodated in future applications of the methodology.) Over time, the optimisation of the network will enhance the capabilities of the network for servicing regionalisation, and should lead to improvements in flow estimates from regionalisation techniques, by driving improvements in data quality in those catchments which are of highest utility for pooling. Similarly, the scientific capacity of the network for regionalisation needs to be safeguarded despite pressure on resources for monitoring. Mishra & Coulibaly (2009) cite several examples of lower accuracy of streamflow estimates resulting from decreased network density. By facilitating judicious rationalisation, the methodology can be used to ensure network contraction does not have deleterious effects on estimation at ungauged sites using the FEH or Low Flows 2000.

An important caveat is that the regionalisation methodologies used herein, while representing widely used design methods, are not the only methods promoted for regionalisation. There is much scientific debate in the international literature concerning which are the most appropriate mechanisms for indexing catchment similarity, and which catchment attributes to use (e.g., McIntyre *et al.* 2005; Yadav *et al.* 2007; Reichl *et al.* 2009), or whether to even use catchment similarity measures as opposed to local data transfer (Merz & Blöschl 2005). Wagener *et al.* (2007) suggest that the difficulty in establishing any common scheme for catchment classification is a result of (1) our limited understanding of how various catchment properties interact to create catchment responses and the choice of the most appropriate metrics to describe them; and (2) partly our inability to measure these structural or hydro-climatic properties of catchments. The results presented in this paper should be therefore be considered one approach to regionalisation and, over time, the importance of gauges which may now be considered of low utility may come to light as hydrological understanding develops. Caution must therefore be adopted, especially where gauges are potentially viewed as redundant. Nevertheless, resource pressures on networks are a reality, and the new methodology represents a pragmatic attempt to employ the current widely used standards in high and low flows regionalisation to guide network evolution strategies. In principle, a similar approach could be used for other regionalisation techniques – the key requirement is that the regionalisation algorithm can effectively be inverted, to assess the value of currently gauged catchments in light of landscape or hydro-climatic variability in ungauged locations.

A further consideration in applying the methodology is that regionalisation potential is only one way to assess strategic importance. A catchment may be of very limited value for pooling, but may prove useful for other strategic goals such as trend detection (Bradford & Marsh 2003). Some sites which are heavily impacted by AIs, while of limited regionalisation value, are needed to understand the ecological impacts of changes in flow regime (e.g., Acreman *et al.* 2009). Clearly, the attributes assembled by the methodology are also highly relevant to these other aims, so provided it is not used in isolation, the method facilitates consideration of other drivers of network evolution. An assessment of operational utility is an over-riding factor which must be considered before redundancies could be addressed. Nevertheless, the technique is designed so that it can be readily integrated with operational utility, as applied in the E & W network review (Davis *et al.* 2010).

The method is designed to be generic and extensible through its modular structure, and it is therefore potentially transferable to other networks. Different scoring schemes and weightings could be applied in different networks, according to the requirements of network managers. Clearly, the method has been demonstrated in a very data-rich environment; in an international context, the UK is privileged with vast quantities of available hydrometric data, catchment descriptors and metadata on data quality. In more data-sparse environments, applying the methodology in totality would be a challenge, although some aspects could be replicated with less data-intensive alternatives. The following paragraph elaborates some considerations on the portability of the methodology.

The catchment utility assessment is predicated on a pooling-group methodology, but similar regionalisation techniques are widespread (e.g., Canada, Zrinji & Burn 1994; Nepal, Rees *et al.* 2006; Austria, Laaha & Blöschl 2007; Australia, Reichl *et al.* 2009). If such methods are unavailable, other means of assessing catchment potential, via spatial characteristics, could also be considered (for example, representativeness of a catchment compared to a wider region, e.g., in terms of land use and elevation; Laizé 2004). The data utility component is based on a quantitative assessment in the present study, which requires metadata on AIs and hydrometric practices, but less data-intensive options could be applied. Assessing AIs requires datasets on abstractions, effluent returns and reservoirs, but information on water management infrastructure is limited in many countries (e.g., see Vörösmarty & Sahagian 2000). A categorical score based on presence/absence of impact types (e.g., the UK Factors Affecting Runoff classification; Marsh & Hannaford 2008) could be used as a low-cost alternative. Second, a HDQ indexing system is needed, as facilitated herein through the GSDQ system, although a simple categorical score was also employed. A similar approach could be applied elsewhere, provided it is applied judiciously by experienced personnel. There are many examples of national hydrometric databases (just two published examples being: New Zealand, Mosley & McKerchar 1989; India, Chowdary *et al.* 2004) which could yield the metadata required to allow such judgements (and possibly even analogues to the GSDQ) to be made.

One additional aspect of the methodology is that it can potentially be used to identify gaps in the current network, e.g., combinations of landscape characteristics which are not well represented in the current network and which could be filled by developing monitoring capacity in ungauged locations. Previous studies have used network appraisal techniques to identify current deficiencies in network coverage (Mishra & Coulibaly 2010). Extending the new method to enable identification of gaps is the subject of ongoing research by the authors, and is beyond the scope of this paper. In principle, the method may facilitate this by enabling the identification of catchments in the ungauged set of targets used to calculate the HCUI and

LCUI, which are currently not well represented in the pool of gauged donor catchments.

CONCLUSIONS

This paper has described a novel methodology for evaluating hydrometric networks for regionalisation, based on widely used pooling-group techniques for high and low flow estimation, and has two components: an assessment of the potential utility of a catchment for regionalisation, and a parallel (but independent) appraisal of the performance of the gauging station draining the catchment. This confers some benefits over previous methods for network appraisal, in that the quality of data being captured is an explicit factor in assessing the utility of gauging stations.

The methodology is applied to a national network of over 1,100 gauging stations in E & W, to demonstrate the efficacy of the methodology in assessing the 'fitness for purpose' of a hydrometric network for facilitating regionalisation. This analysis has shown that the methodology can be used to identify priority gauging stations for hydrometric improvement – where upgrades in performance would yield the greatest benefits for regionalisation and, over time, improve the credibility of regionalised flow estimates – and to identify stations which are contributing little value to regionalisation studies, which could potentially be decommissioned without deleterious effects on the capacity of the network for enabling flow estimation at ungauged sites.

One of the key advantages of the method is that it has a scientific basis by focusing on regionalisation – thus enabling scientific goals to be prioritised in network evaluation, in addition to the more traditional bias towards operational priorities – although, clearly, this basis is limited by the range of applicability of the pooling group methods used. However, the core of the method is a generic and flexible framework which could potentially be transferable to other networks around the world where different pooling-group techniques are used. Used with suitable caution (given the focus on specific pooling-group methodologies) the method can be rapidly applied as a screening tool to large networks, and translates into simple messages which resonate with managers, researchers and end-users. As the approach focuses primarily on regionalisation, other network drivers (both strategic and operational) should be considered alongside this methodology. Nevertheless, the key principles, datasets and methods are highly complementary to other uses of hydrometric networks, and extensible to other drivers of network evolution.

Ultimately, the methodology ensures that, against a background of increasing pressures on hydrometric networks, the benefit of existing monitoring is maximised; moreover, that strategic and scientific needs can be safeguarded and, in fact, promoted, when reviewing the utility of hydrometric networks.

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