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Reference Hydrologic Networks II. Using Reference Hydrologic Networks to assess climate driven changes in streamflow

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Abstract: Reference Hydrologic Networks (RHNs) can play an important role in monitoring for changes in the hydrological regime related to climate variation and change. Currently, the literature concerning hydrologic response to climate variations is complex and confounded by the combinations of many methods of analysis, wide variations in hydrology, and the inclusion of data series that include changes in land-use, storage regulation, and water-use in addition to those of climate. This paper presents three case studies that illustrate a variety of approaches to the analysis of data from RHNs and uses these case studies, plus a summary of studies from the literature, to develop approaches for the investigation of changes in the hydrological regime at a continental or global scale and particularly for international comparison. The paper presents recommendations for an analysis framework and the next steps to advance such an initiative. There is a particular focus in the paper on the desirability of establishing standardized procedures and methodologies for both the creation of new national RHNs and for the systematic analysis of data derived from a collection of RHNs.

Key words reference hydrologic networks; trend analysis; climate change; streamflow

Introduction

Assessing the impacts of climate variations on the flows of streams and rivers is a challenge of great magnitude and importance. The response of a particular watershed to climatic change integrates not only the climate input, but also direct human influences such as land-use changes and changes in storage, as well as change and variability in the hydrology of the watershed. Confounding this are the many hydrological variables and indices that could be assessed whose relevance is not necessarily consistent amongst watersheds. Also, published studies have used different periods of data and different statistical analysis methods. The literature on the hydrologic response to climate variations is therefore complex and often ambiguous. Assembling and summarizing a variety of trend studies across diverse regions is neither simple nor does it provide the necessary clarity about hydrological response to climatic change. Policymakers are unlikely to consult hydrological research studies reported in the technical literature, and if they do, they are faced with a proliferation of messages and no clear consensus of historical changes.

There is clearly a need to develop a synthesis of results obtained using a common analysis protocol such that the way in which a variety of watersheds respond to climate can be presented in a manner that overcomes the confusion of collected studies. We believe that Reference Hydrologic Networks (RHNs) can be used to overcome at least some of these problems.

Streamflow data collected from RHNs can be used to quantify changes in the hydrological regime that may occur, for example, as a result of climate change (Hannah et al. 2011). In the context of climate change, there is a pressing need for RHNs, which attempt to filter out human influences by focusing on those catchments with undisturbed flow regimes that are gauged by stations that produce reliable hydrometric data. In a companion paper, Whitfield et al. (2012) give detailed descriptions of the commonalities and differences associated with RHNs that have been established in a number of countries where they have been used to monitor and identify any changes or patterns in the hydrological regime (see, for example, Lins and Slack 1999, Burn and Hag Elnur 2002, McCabe and Wolock 2002, Burn et al. 2010, Stahl et al. 2010, Hannah et al. 2011).

Gauging stations forming an RHN should consist of catchments that: i) are near-natural; ii) are unregulated; iii) contain long record lengths; iv) are active gauges; v) have good quality data; and vi) have adequate metadata (Pilon and Yuzyk 2000, Whitfield et al. 2012). Many RHNs will have been designed to meet most or all of these criteria. RHNs have been established in several jurisdictions as a subset of the existing national hydrometric network, including the United States (Slack and Landwehr 1992), Canada (Brimley *et al*. 1999, Harvey et al. 1999) and the United Kingdom (Bradford and Marsh 2003). There have also been several studies that report on the assembly of a data set of gauging stations with RHN-like characteristics including Stahl et al. (2010) for Europe, Wilson et al. (2010) for a pan-Nordic network and Rennermalm et al. (2010) for a pan-Arctic network of gauging stations. Hannah et al. (2011) provide a useful discussion of the importance of data from RHNs as well as an interesting discussion of some of the challenges associated with establishing and maintaining a national RHN.

For comparative purposes, hydrologic variables used in trend studies should be consistent. While many of the existing studies focus on hydrological variables that are regionally appropriate or convenient, there is not a universal hydrologic climate change signature that manifests itself in the same way across different geographical domains. In general terms, the variables that should be considered need to be relevant to the hydrology of the region. As the world is hydrologically complex, it is not possible to select a single hydrological variable that meets these criteria in each and every region. However, a common framework is needed so that comparisons are made on variables that are considered appropriate across a range of environments.

In addition to appropriate streamflow data and variables, the use of sound statistical data analysis techniques is required to identify any changes in the hydrological variables and to quantify the magnitude of any changes that are identified. To assist with the comparison of results from different national RHNs, it is essential that there be some level of commonality in the analysis approaches and hydrological variables used in the analyses (Rennermalm et al. 2010).

The objective of this paper is to evaluate the usefulness of RHNs in assessing the impacts of climate change on the hydrological regime on a regional, national, and international basis. The paper presents several examples of national RHNs and their use for detection of hydrologic changes related to climatic changes. The examples are drawn from RHNs located in the United Kingdom, the United States, and Canada. A section then explores lessons learned from these case studies as well as from a large selection of studies from the literature, and includes a summary of commonly used hydrologic trend testing methods along with suggestions on increasing standardization of the methods. Finally, the paper outlines the steps that could facilitate an international effort to conduct a coordinated assessment of changes in the hydrological regime using data from RHNs applied on a larger spatial scale than is currently possible. This effort could be very useful for future assessments of the impacts of climate change upon the varied hydrology of the world.

Case Studies

The following subsections contain three examples from our use of RHN data for the purpose of assessing climate driven change; they are typical of the literature on hydrologic response to climate change. The first case study uses data from the United Kingdom the second uses data from both Canada and the United States and the third uses data from Canada. These examples involve the use of a variety of different hydrological variables and different techniques for analysis and interpretation. The research work for each of the examples was conducted independently by a subset of the authors of this paper and there has been no explicit attempt to standardize them; full presentations are available elsewhere (Hannaford and Marsh 2006, 2008, Hannaford and Harvey 2010, Hodgkins and Dudley 2006, Burn 2010). These examples reflect only some of the diversity of approaches currently being used to determine trends. The Standardization of Climate-Related Hydrologic Trends section of the paper summarizes some of the characteristics for 128 hydrological trend studies present in the literature. The three examples presented herein, as well as the summary of studies in the standardization section, identify many inconsistencies in the use of data and statistical methods in the hydrologic trend literature. The lack of consistency has undoubtedly contributed to the ambiguous messages regarding the response of hydrological systems to climate change, as discussed in the introduction. To this end, the standardization section identifies more consistent approaches that can be applied on a larger spatial scale than has been previously possible.

Case study #1 – The United Kingdom (UK) Benchmark Network

The United Kingdom Benchmark Network contains over 130 gauging stations that have been identified for use in the detection, monitoring, and assessment of climate change (Bradford and Marsh 2003). The Benchmark Network has been used extensively for trend analysis since its inception in 2003 – the following case study combines the results of three separate, but related, studies that have used the network (Hannaford and Marsh 2006, 2008, Hannaford and Harvey 2010).

Hydrological Variables

The hydrological variables used in this case study were chosen because they are commonly used in the UK for comparing streams, and since they are used in engineering applications. Hannaford and Marsh (2006) focused on a water resources/low flows perspective, and considered widely-used indicators of annual runoff and low flow magnitude (7-day minimum; 30-day minimum) and duration (prevalence of low flows, i.e. number of days below Q90 and below Q70). Note that Q90 denotes the value from the flow duration curve that is exceeded 90% of the time. In a companion study, Hannaford and Marsh (2008) focused on flooding issues, and considered indicators of high flow magnitude (10-day maximum; 30-day maximum) and duration (prevalence of flows above Q10), as well as a true indicator of flood magnitude, the annual maximum instantaneous flow (Annual Maximum), and frequency (of Peaks-Over-Threshold, POTs). Hannaford and Harvey (2010) considered seasonal average flows, using the following standard classification of UK seasons, widely used and endorsed by the UK Meteorological Office: winter (Dec – Feb), spring (Mar – May), summer (Jun – Aug) and autumn (Sep – Nov).

Analysis Methods

The analyses conducted on the UK Benchmark Network have been carried out in several separate studies over a seven year period, so a number of different analysis methods have been applied. All studies used the Mann-Kendall non-parametric test for trend (Mann 1945, Kendall 1975) and the Sen slope (also known as the Thiel-Sen slope and the Kendall-Theil robust line) to compute the magnitude of trends. This slope is computed as the median of all possible pairwise slopes in each data set (Helsel and Hirsch 1992). Hannaford and Marsh (2006, 2008) also use linear regression to compute significance and magnitude of trends. Significance levels for the regression gradient and Mann-Kendall test statistic were established using both the conventional method and a permutation test, which does not require any distributional assumptions to be made (Kundzewicz and Robson 2004). An additional advantage of the permutation test is that resampling can be carried out in blocks, which enables serial correlation to be accounted for. Further details of the permutation testing framework are provided in Hannaford and Marsh (2006, 2008). However, long-term persistence (LTP) was not accounted for in either study. Spatial correlation was not addressed explicitly as a major part of either of these studies: Hannaford and Marsh (2008) did consider whether the high flow trends were field significant at a national scale (using the approach of Douglas *et al*. 2000), but regional significance testing was not carried out.

More recently, Hannaford and Harvey (2010) applied an alternative methodology (following Stahl et al. 2010), whereby the magnitude of the Sen slope was used to assess trends; no significance testing was applied, as the aim was to examine spatial variation in the observed trends, rather than attribute statistical significance. Catchment areas were used in this study to present results, to show the effect of the varying catchment size in UK benchmarks (see Figure 1).

In the studies of change in high and low flows, two study periods were used to reflect a trade-off between record length and network density, but the study periods used vary: Hannaford and Marsh (2006) considered 1963 – 2002 and 1973 – 2002, whilst Hannaford and Marsh (2008) considered 1959 – 2003 and 1969 – 2003. In the later study on seasonal trends, Hannaford and Harvey (2010) employed an updated period of 1969 – 2008.

Results

The results of the trend analysis for the network of stations are summarized in Table 1. As different methodologies and study periods were used, an arrow is used to indicate compelling evidence of change (i.e., consistency of strong trends in this direction when using trend magnitude, or in terms of number and strength of significant trends when significance was tested), over the various study periods, whilst a very mixed pattern or no compelling evidence is indicated with a hyphen.

Conclusions from Case Study

In general, the evidence points to overall increases in river flow in many areas of the UK. Annual runoff has increased, and it is likely this is driven by observed increases in autumn and winter runoff. Similarly, high flows have increased, although evidence for flood magnitude trends (in terms of annual maximum flow) are less compelling than changes in high flow magnitude, duration and frequency. There is very limited evidence for any pronounced change in low flows over the study periods. Similarly, summer and spring runoff trends are rather weak and regional patterns very mixed. One of the main findings of these studies is the geographical variation in observed trends. Strong increases in runoff and high flows are generally confined to upland, maritime-influenced catchments in the north and west. Hannaford and Marsh (2008) found strong correlations between high flow trends and the North Atlantic Oscillation index (NAO), so observed increases in high flows may reflect a shift towards a more predominantly positive NAO over the period of study, bringing wetter weather to areas exposed to westerly airflows. In the lowlands in the south and east of England, in contrast, the evidence for trends in any part of the regime is weaker, with very mixed patterns, and there is certainly limited evidence for any decrease in runoff in these areas. Hannaford and Marsh (2006, 2008) and Hannaford and Harvey (2010) use selected long non-RHN records to put the recent trends in a long-term context, and note that recent trends may not be representative of trends over longer periods. Despite the recent increase in high flows, the evidence for any compelling long-term increase in flood magnitude in the UK is weak (Hannaford and Marsh 2008, Marsh and Harvey, in press).

Case Study #2 – Assessing a geographic area using United States Hydro-Climatic Data Network and Canadian Reference Hydrometric Basin Network

Daily mean streamflow data from rivers that drain relatively natural watersheds in eastern parts of the United States and Canada were used for this study, which includes results from Hodgkins and Dudley (2006) plus additional analysis. In the United States, data were obtained from the U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN), which includes data from 1,659 streamflow-gauging stations across the USA (Slack and Landwehr 1992). This network contains stations with good quality data whose basins are relatively free of human influences such as regulation, diversion, land-use change, or extreme ground-water pumping. Canadian streamflow data were obtained from the Canadian RHBN, which has similar criteria to the HCDN network (Brimley et al. 1999). The selected stations were chosen because the interest was in changes in the timing of winter-spring streamflows in eastern North America (east of 100º west longitude, north of 41° north latitude) that are substantially derived from snowmelt runoff. It was important to use data from both countries because of the large annual snowpack and potential for sensitivity to small changes in winter-spring temperatures on both sides of the border. Some 179 gauging stations met the criteria of this study including having at least 50 years of data through 2002 (Hodgkins and Dudley 2006). The number of appropriate stations fell to 140, 81, 41, and 25 for periods of 60, 70, 80, and 90 years, respectively.

Hydrological Variables

The center of volume date (Hodgkins and Dudley 2006) was used for a measure of streamflow timing during the annual period of snowmelt runoff at the selected streamflow-gauging stations. To compute this date, daily flow volumes from January 1 through June 30 were summed and the date from the start of the season by which half or more of the volume flowed by a gauging station was computed.

Analysis Methods

The Mann-Kendall non-parametric test was used to test for significance of temporal trends and the Sen slope was used to compute the magnitude of trends. There must be no serial correlation for the Mann-Kendall test p-values to be correct (Helsel and Hirsch 1992). However, the existence of serial correlation does not affect the estimated value of the Sen slope (Yue et al. 2002). Serial correlation was analyzed by computing the Durbin-Watson statistic on the residuals of the Sen slope lines of data sets that had a significant temporal trend ($p < 0.1$). There was no significant positive serial correlation ($p < 0.1$) in the winter-spring center of volume dates from 1953-2002. Field significance for results was calculated by multiplying the minimum local p-value for a region by the number of local tests in that region. This method closely approximates the Walker test; this test avoids problems associated with some other field significance tests (Wilks 2006). The influence of long-term persistence on trend significance (Cohn and Lins 2005, Koutsoyiannis and Montanari 2007) was not considered. Estimates of the magnitude of trends vary little between tests that consider long-term persistence and those that do not (Cohn and Lins 2005).

Results

Approximately 32 percent of stations north of 44° north latitude had significantly earlier ($p < 0.1$) flows over 50, 60, 70, and 90 year periods through 2002; 64 percent had significantly earlier flows over the 80 year period; there were no significantly later flows for any time period examined (Figure 2a for the 50-year period, from Hodgkins and Dudley (2006)). In areas of eastern North America between 41° and 44° N, few stations had significantly earlier dates for any of the time periods studied. Results were field significant ($p = 0.06$) for the region north of 44° north latitude.

Flows for all stations north of 44° became earlier by an average of 6.1, 4.4, 4.8, 8.6, and 6.5 days for the 50 through 90 year periods, respectively. Most streamflow-gauging stations north of 44° north latitude had earlier dates from 1953 to 2002 (Figure 2b, from Hodgkins and Dudley (2006)). Some areas had a mix of earlier and later dates, including far eastern Canada (Nova Scotia and Newfoundland), and the western part of the study area in the USA (central Wisconsin and southern Minnesota). The most common change was five to ten day earlier streamflows.

Conclusions from Case Study

Earlier snowmelt runoff is likely the primary cause of changes over time toward earlier winter-spring center of volume dates for rivers in eastern North America north of 44° (Hodgkins and Dudley 2006). Changes in precipitation patterns could also contribute to earlier flows. Warmer air temperatures would cause earlier flows through earlier snowmelt and increased ratios of winter rain to snow. Studies in North America using historical data have shown that air temperature in the few months before and during snowmelt explain much of the interannual variability in the timing of snowmelt-related streamflows (Stewart *et al.* 2005, Hodgkins *et al.* 2003). Some 52% of the interannual variability of center of volume dates in the far northeastern USA was explained by March through April air temperatures; January precipitation (the month with the highest correlation with center of volume data) explained 14% of the variability. Déry et al (2009) showed that the center of volume date in western Canada is a function of both the temperature and the amount of snowpack. When snowpack is constant, the date becomes earlier with increased temperature; when the snowpack increases, the date becomes later. Increased snowpack is a function of air temperature and (or) precipitation changes and other physical changes such as solar radiation, wind, and humidity (Hodgkins and Dudley 2006). Later flows documented in the USA and Canada may result from changes in precipitation patterns or from increased snowpack in these areas.

Case Study #3 - Canadian Reference Hydrometric Basin Network

The Canadian Reference Hydrometric Basin Network (RHBN) contains over 200 gauging stations with a minimum record length of 20 years that have been identified for use in the detection, monitoring, and assessment of climate change (Brimley et al. 1999). This case study uses a sub-set of 109 stations with a record length of at least 40 years. Although the 109 stations are drawn from across Canada, there is a southern bias in the sub-network due to the lack of long duration records in the Canadian north. Analysis on the stations was done using three (common) analysis periods: 1949 to 2008 (60 years);

1959 to 2008 (50 years); and 1969 to 2008 (40 years). Because of missing data for some stations and some variables, there were generally less than 109 stations available for the 50 and 60 year analysis periods.

Hydrological Variables

A total of 17 hydrological variables were analyzed and include: monthly and annual flow; annual maximum flow magnitude and date of occurrence; and annual minimum 7-day average low flow magnitude and date of occurrence. The collection of hydrological variables were selected to assess the trend characteristics of diverse elements of the hydrological regime of the study area including measures of the average water availability and its seasonal variability, the magnitude and timing of high flow events and the magnitude and timing of low flow events. This collection of hydrologic variables was chosen because they are commonly used in Canada to compare and contrast properties of the many hydrologic regimes. These 17 variables are also commonly used in engineering assessments.

Analysis Methods

The Mann Kendall test was used to identify trends in hydrological variables. The presence of a positive serial correlation in a data set can increase the expected number of false positive outcomes for the Mann-Kendall test (von Storch and Navarra 1995). The version of the trend test used incorporates a correction, developed by Yue et al. (2002), for serial correlation in the data. The calculated trend statistic can be used to determine the significance of a trend in a data set, which is referred to as the local significance level for an individual site. For a collection of sites, the global (or field) significance of the individual results at the collection of sites is evaluated using a bootstrap resampling technique (Burn and Hag Elnur 2002). Field significance allows the determination of the percentage of tests that are expected to show a trend, at a given local (nominal) significance level, purely by chance. The resampling technique determines the critical value for the percentage of sites exhibiting a trend and addresses the impacts of intersite correlation. Based on this critical value, it is possible to determine whether the observed number of trends exceeds what is expected to occur by chance. Long term persistence

(LTP) was not accounted for in the trend analysis conducted for this case study. Further details on the trend detection methodology used can be found in Burn et al. (2004).

Results

The results of the trend analysis for the network of stations across Canada are summarized in Table 2. The results in Table 2 show the direction of trends for hydrological variables that demonstrate field significance calculated for the entire network (i.e., variables for which there are a significant number of significant trends). Increasing and decreasing trends are analyzed separately and there can therefore be variables with both increasing and decreasing arrows (implying that for the variable there are an unusual number of increasing trends and an unusual number of decreasing trends). The results are presented for the 10% significance level (both local and field significance) because the intent of the analysis is exploratory and thus a less restrictive significance level was appropriate.

Conclusions from Case Study

Changes are occurring in the hydrological regime of the case study area. Peak flow magnitudes are generally decreasing and occurring earlier in the year; the latter is related to an earlier onset of the spring freshet. Low flows are both increasing and decreasing with different patterns occurring in different parts of Canada. The changes in the low flow regime can be partially explained by the hydrological processes that lead to low flow conditions and generally result in increasing low flows for the winter and decreasing low flows for the summer/fall. There is a shift in timing of streamflow with an increase in winter/early spring and a decrease in late spring/summer. These results are consistent with other studies in Canada (Zhang et al. 2001, Burn and Hag Elnur 2002, Yue et al. 2003, Ehsanzadeh and Adamowski 2007, Khaliq et al. 2008, Cunderlik and Ouarda 2009). Updates of trend analysis in this work using the most recent data (to 2008) provide additional insights into changes that are occurring and reveal increases in winter flow, especially January, and significant decreasing trends in low flow for the south-west portion of Canada (see also Burn et al. 2010).

Standardization of Climate-Related Hydrologic Trend Studies

Consistent hydrologic data, variables, and analysis methods are required to facilitate the comparison of hydrological trends among gauging stations at regional, national, and international levels. Greater standardization will ensure that trend analyses can be carried out consistently and results compared between Reference Hydrologic Networks, to facilitate judicious assessments of the evidence for climate-driven change upon the hydrological cycle – for example, in future Intergovernmental Panel on Climate Change (IPCC) reports. The three example case studies of using RHNs for assessing climate driven change, and the 128 studies reviewed for this paper, have both commonalities and differences in: i) the nature and type of data analyzed; ii) the data analysis period(s) used ; iii) the selection of hydrologic variables; and iv) the trend analysis methods used. The following sections discuss each of these issues in greater detail in the context of moving towards the development of standardized approaches. The role of RHNs is re-evaluated in light of the case studies and literature assessed, and data issues are also considered (e.g., the effect of basin scale upon responses to climate change).

The Role of Reference Hydrologic Networks

Much of the published literature on historical hydrological trends does not make a clear distinction between trends due to changes in climate, land-use, or water use. RHNs should play a more prominent role in hydrological trend studies as RHNs function as a control for non-climatic anthropogenic influences. The 128 studies of climate change effects on hydrology summarized in Table 3 illustrate the scope of this issue; only around 40% of the studies used stations that were either part of an RHN or were selected based on criteria similar to those used to identify an RHN. A complete citation for each of the 128 studies that are summarized in Table 3 is contained in the Supplemental Material. It is a concern that the majority of the 128 trend studies from across the globe, summarized in Table 3, have not used data from an RHN, or from an RHN-like network, as a control against land-use, regulation, or water-use effects.

RHNs, by their guiding principles, enable predominantly climate related trends to be discerned from the impacts of other disturbances. In two of the example case studies presented herein, national RHNs were utilized and in one example, similar national RHNs in Canada and the United States allowed for cross border analyses to be completed. The UK case study used some non-RHN stations with long record lengths. In this case, the longer term records were used to better understand the changes in the RHN stations from the perspective of longer term patterns and cycles, and the non-RHN sites were kept apart from the statistical analysis so they were not being compared with RHN sites.

Four recent studies explicitly explored the impacts of RHN stations on the results of trend analysis. Hannaford and Marsh (2006) report on the 30-day minimum flow time series for the River Thames in the UK. There is a significant decreasing trend in the 121 year record for this site. However, when the record is naturalized by accounting for non-returning abstractions upstream of the gauging station, the trend direction is reversed. The naturalized flow sequence in comparison to the gauged record can be viewed as being analogous to comparing an RHN station with a non-RHN station, dramatically demonstrating the importance of using RHN stations in trend analysis. Hodgkins et al. (2007) evaluated streamflow trends for RHN stations, stations gauging urbanized streams and stations gauging regulated streams. They found generally different results for the urbanized and regulated streams in comparison to the results for RHN stations. Vogel et al. (2011) examined changes in flood frequencies for close to 20,000 stations in the USA. When the results were separated in accordance with the regulation status of the station (regulated, non-regulated, and RHN), there were dramatic differences in the magnitudes of the temporal changes observed, further illustrating the confounding influence of land-use change and regulation of streams. Finally, Lorenzo-Lacruz et al. (2012) conducted an analysis of streamflow trends across the Iberian Peninsula. Whilst the study did not use an RHN *per se*, regimes were classified into three categories (natural, regulated and highly regulated rivers). Whilst river regulation did not affect the overall sign of trends over the study domain, it did amplify the magnitude of trends and had a pronounced effect on seasonality of streamflows.

Data and Scale Issues of Reference Hydrologic Networks

Standardization of hydrologic trend studies implies that all gauging stations included in the analyses should be part of a national RHN and that common, or at least similar, criteria should be used in the establishment of each RHN. The latter attribute, while desirable, may not be completely attainable given the different national agencies/organizations involved in establishing national RHNs as well as possible differences in data collection protocols for different countries. It is encouraging that most of the current national RHNs have been developed using similar criteria.

An issue influencing the interpretation of trend results is the density and geographical patchiness of RHNs. Woo and Thorne (2006) point out that the density of stations in the Canadian RHBN is limited, especially in the north, with most of the hydrometric stations located in southern portions of Canada. A decline in the number of active streamflow stations combined with the short record length from most northern rivers render it difficult to distinguish long-term trends from medium-term variability. In the UK, the primary issue is that the lowland areas of southern England are very densely populated, and attempting to define truly “pristine” RHN catchments would probably mean there would be no coverage in this area (Bradford and Marsh 2003); there is therefore a need to tolerate some degree of disturbance, which then means national-scale results must be viewed with caution.

As noted by Whitfield et al. (2012), some researchers advocate selecting for trend studies only those gauging stations with a drainage area within a defined size range. It is clearly important that scale issues are addressed in the interpretation of trend analysis results as different hydrological processes operate across a range of scales (Blöschl and Sivapalan 1995) and climate change may cause differing responses at different scales. However, it may frequently not be practical to restrict analysis to stations within a defined drainage area size range because of the limited number of RHN catchments with long term records.

Analysis Period

An important aspect of hydrologic trend studies that requires standardization is the analysis period. The analysis periods used in the case studies presented herein, and many of the studies reviewed in Table 3, generally had a starting year around 1950 or later with an ending year corresponding to the last year of data availability at the time that the analysis was conducted. The selection of an analysis period often represents a trade-off between temporal versus spatial coverage with more stations being available for the shorter (more recent) analysis periods. The case studies used different (common) analysis periods to explore the temporal variation in trend results and examined longer records to put short-term trends into a fuller historical perspective.

Trends are invariably sensitive to the analysis period used. Many authors have commented on the effects of “clustering” of notably wet and dry years within series and on the limitations of short study periods; trends over short periods may reflect part of longer-term quasi-periodic oscillations (Kundzewicz and Robson 2004, Chen and Grasby 2009). The influence of relatively short periods on trend responses is particularly important in the context of patterns of multi-decadal variability driven by large-scale teleconnections (Svensson et al. 2006, Woo and Thorne 2008). In the UK case study, the influence of changes in large-scale atmospheric circulation (specifically, a shift towards a more prevalent positive NAO) over the analysis period was shown to be influential. Similar concerns exist for other large scale climate system features (ENSO, PDO, AMO, etc).

While the end of the analysis period is generally the most recent year for which data are available, McCabe and Wolock (2002) describe a “moving window” approach that involves examining many analysis periods of differing lengths and obtain interesting insights from this analysis (see also Wilby (2006), Hannaford and Harvey (2010) and Rennermalm et al. (2010)). The need to select common analysis periods from different national RHNs will undoubtedly result in the exclusion of the most recent data for some of the locations and the exclusion of stations with short periods of record. A balance is needed between obtaining complete overlap with the records for all sites and having a longer analysis period with some stations having missing data for part of the analysis period. Given that the majority of RHN records are from the latter half of the twentieth century, there is also an important role for studies of long (>100 year) streamflow records (e.g., Schmocker-Fackel and Naef 2010, Marsh and Harvey in press). These may be subject to anthropogenic disturbance and may contain inhomogeneities, (e.g., owing to changes in measurement practices over time), but they should still be used to complement

RHN studies, enabling recent trends to be placed in a fuller historical context. This is particularly important in the UK where the majority of gauging stations have records beginning in the 1960s and 1970s and trends may be affected by dry sequences near the start of the record and a very wet sequence near the end. The lack of long records also underlines the importance of data stewardship to preserve such datasets where they exist, and in efforts to unearth more. Effort could also be put into expanding the timeframe of RHN analyses through using reconstructed data (e.g., Wilby 2006) or, for a very long perspective, using analogues such as documentary evidence (e.g., Brázdil *et al*. 2006) or paleo reconstructions, though these methods introduce additional uncertainties.

Variables to Analyze

Since data are available at a daily temporal resolution for most RHNs, establishing a common set of hydrological variables to analyze is likely to be the easiest step in the standardization process. There is consensus from many trend analysis studies that the hydrological variables investigated should encompass a comprehensive set of measures of the hydrological regime for the catchments in a defined area. Common variables to two of the three case studies were annual and monthly/seasonal streamflow, representing overall measures of water availability. Additional hydrological variables often included are measures of extremes; high flow, low flow, or both. This can include measures of the magnitude, duration, timing and/or frequency of extreme flows. The case studies herein, and other studies (e.g., Lins and Slack 1999, Burn and Hag Elnur 2002, Stahl et al. 2010), indicate that the consideration of an extensive collection of hydrological variables is essential to properly characterize the nature of changes occurring in the hydrological regime of the catchments within a study area. The selection of appropriate hydrological variables for studies seeking to detect and attribute climate change needs to be carefully considered. The variables that are selected need to be reflective of the specific hydrological type of a region, as demonstrated by the use of a snowpack-based indicator in the second case study. Even in a small country like the UK, regimes vary significantly; whilst all watersheds are predominantly affected by precipitation rather than snow/ice, there are major differences in storages due to catchment geology, which may influence the response to any climate signal (Laizé and Hannah 2010).

Specific variables can be very useful in examining particular issues. It may not be desirable to standardize all hydrologic variables because different hydrologic processes dominate in different areas. For example, annual low flows occur in the winter in many northern rivers (in the northern hemisphere) due to long periods of snow and ice cover; in more southern areas, annual low flows occur primarily in the summer and fall. This is particularly true from a global perspective where hydrologic process variation is very much embedded within the climate system. Many favoured hydrologic variables, such as monthly flows, are not relevant in a global mix of perennial and ephemeral rivers. It may be more appropriate to select specific variables for individual hydrologic regimes and only compare within that regime rather than to compare variables that are not specific between different regimes, as carried out in some regional studies (e.g., Hisdal *et al*. 2001, Khaliq *et al.* 2008, Déry *et al.* 2009). An additional consideration is that, in hydro-climatic records, high background variability results in a low signal to noise ratio that may obscure the identification of trends. This could mean that climate changes may be exerting an influence on water availability and infrastructure before they can be formally detected, implying the need for indicators that can increase the signal to noise ratio (Ziegler *et al.* 2005, Wilby 2006). Such indicators need to be used with similar caution; indicators need to be specific and robust within the local hydrology and only reported where they are informative.

Trend Analysis Methods

Hydrologic trend studies have used a variety of statistical analysis methods for computing trend significance and/or magnitude. The approaches used to identify trend significance in hydrologic variables generally involve either some version of the Mann-Kendall test or linear regression. From the 128 studies summarized in Table 3, 70% used the Mann-Kendall test, 26% used linear regression and 11% used some other technique (several studies used multiple techniques, resulting in the values not summing to 100%). Many of the studies in Table 3 (45%) have handled serial correlation (short term persistence) in the data through a form of prewhitening of the data or block resampling to account for the effects of serial correlation. Only 6% of the studies accounted for long term persistence. Field significance was applied in 22% of the studies summarized in Table 3. Trend magnitudes were calculated using either linear regression or, more commonly, through the estimation of the Sen slope.

Traditionally, an approach based on the Mann-Kendall test was used in analyses of trend significance with refinements being made to the basic methodology to reflect the effects of (short term) serial correlation and cross correlation. Cohn and Lins (2005) demonstrated that trend tests yield very similar estimates of trend magnitudes with and without the presence of short and long term persistence; however, concern about the presence of long term persistence in hydrologic data series calls into question the validity of data independence, which is a basic assumption of statistical significance tests (Koutsoyiannis and Montanari 2007, Hamed 2008, Chen and Grasby 2009). In addition, Clarke (2010) argues that there is exaggerated attention given to the results of non-parametric statistical significance tests, and that there should be greater attention to developing parameterized models and calculating uncertainties in model parameters. As a result, several studies (Milly et al. 2005, Milliman et al. 2008, Hodgkins 2009, Stahl et al. 2010) have estimated only the trend slope for catchments and examined the geographic coherence and spatial patterns of trend slope magnitudes and avoided the issue of statistical significance. There is not yet a clear consensus in the literature as to which of these general approaches to use; this issue of reporting statistical significance will need to be resolved in any coordinated international initiative to compare RHN studies.

Most of the methods that are presently being used for assessing climate change trends in hydrology make the assumption of monotonic change. This is generally a poor assumption for non-linear systems, and coupled with the patterns of climate system variation supports the need for further research into detection methods that can better separate and assess these non-linear signals. There is also a need to examine time series for abrupt changes in streamflow (e.g. McCabe and Wolock 2002, Villarini et al. 2009) and to explore the factors causing the temporal changes in streamflow.

Next Steps

As outlined in the discussion above, there are several unresolved issues in developing standardized data and methodology that should be addressed before a more comprehensive analysis of hydrological trends and variability related to climate change is undertaken. Before moving the process to a continental or near global scale, more national RHNs must be developed. Standardization of specific hydrological variables, where meaningful, is needed for analysis and standardization is needed for the trend analysis methodology used. One potential avenue for reaching consensus and collaboration on these issues is to hold a special session at an international conference that will bring together experts in this area. While such an approach would be useful in initiating such a process, there remains a place for the involvement of the International Hydrology Program (IHP) or the Commission on Hydrology of the World Meteorological Organization (WMO). These organizations may be helpful for promoting the need for more national RHNs and for ongoing collaboration of experts, following on from precedents such as the publication of WMO/UNESCO-IHP guidelines on trend testing methods (Kundzewicz and Robson 2004), which followed an international workshop held on the topic. One starting point may be to attempt a standardized analysis across those areas that currently have well developed RHNs defined using relatively similar criteria (i.e., North America and parts of Europe such as the UK and the Nordic countries). Such an approach could be useful in "tuning" an effective standardization approach that could then be applied globally as more RHNs are developed and mature.

Policy makers need to become more confident with the results of hydrological change detection and attribution studies. Standardization and intercomparison of approaches could be useful in approaching this issue. While true standardization of methods will not be possible until consensus on an appropriate method is reached, intercomparison studies of widely used methods applied to standardized data sets would provide a useful comparative basis. The use of RHN catchments would allow for control of non-climatic anthropogenic influences such as land use change, regulation, and water abstractions.

There is a need to develop documentation for users (scientists, resource managers, and others) so they have access to guidance on how to best use reference stations and networks in trend detection studies. As part of this documentation, there is thus a need for:

1. Documentation of trend statistics for selected reference stations for specific time intervals using methods of trend detection that are appropriate for these types of data, including common assessment tools/code. This might include

published statistics that users could then use as a reference for their analysis and versions of code. Alternative and newly developed methods could then be compared using these “baseline” reference data sets.

2. A common approach for “hydrologic typing” needs to be documented since hydrological process differences have a large role in how systems respond to climate. Perhaps this entails documentation of hydrologic variables that are useful for different hydrological regimes (perennial, ephemeral, pluvial, nival, glacial, etc.).
3. There should be a common interchange access format that supports data sharing, or conversely assessment software needs to be able to access multiple sources. The simplest route forward would be for each contributor to exchange data in a common format, which would support metadata and information, and this would allow each country to develop tools to interact with their national data and the international data without translation. Studies reported in the literature should be shared in this format as supplementary data or provided to the Global Runoff Data Centre (GRDC) as a ‘specimen’ data set.

Such developments would help the user ensure their data are suitable for its intended purpose and their assessment approach is comparable to those in common practice. This will support better interpretation of the data from these and other networks. Many small and/or less-developed countries depend on the global community for techniques, training and shared experience.

Summary and Conclusions

Reference Hydrologic Networks are effective data sets for the identification of the impacts of climate driven changes on streamflow. The three case studies presented in this paper illustrate a variety of changes that have been found in stations drawn from different national RHNs. The use of data from stations that are part of a national RHN assists with the attribution of the causes of trends by eliminating or minimizing many possible causes, such as reservoir regulation, land-use changes, or changes in the rate of withdrawals from the catchment. The review of 128 hydrologic trend studies showed that only a minority of studies explicitly controlled for these direct anthropogenic watershed changes.

There is a need for either more national RHNs and/or for an RHN-like screening process to be applied on a larger scale, perhaps using data held in a global database, such as the Global Runoff Data Centre (GRDC) in Koblenz, Germany. There are also several methodological trend testing issues to be resolved including the hydrological variables to be analyzed, the analysis period to be used and, probably the most contentious issue, the usefulness of the concept of statistical significance in trend testing. Should the geographic coherence of trend magnitudes from gauged streams be the primary measure of trends? Since there is no clear consensus in the literature as to the most appropriate type of analysis to apply, it is recommended that a special session of an international conference be organized with the goal of resolving some of the issues outlined in this paper. Such a meeting could be held under the auspices of the International Hydrology Program (IHP) or the World Meteorological Organization (WMO). Another pragmatic way forward advocated in this paper is an intercomparison of trends from across several existing, well-established reference hydrologic networks in North America and Europe, using consistent analysis methods, as a prototype for future efforts to use standardized trend testing methods on RHNs at a larger spatial scale.

Historical assessment of climate related hydrologic changes is critical to understanding potential future changes and impacts. International hydrologic reference networks, that include catchments from a wide variety of climatic, topographic, and ecological regions, can form the basis for a wide variety of intercomparison studies of hydrological trends. With international cooperation and leadership, an established and documented international hydrologic reference network data set would exist that could serve as the basis for information on historical hydrological trends in future Intergovernmental Panel on Climate Change (IPCC) assessment reports.

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Table 1 Summary of Trend Results for data from 130 reference hydrometric stations from the UK Benchmark Network

Hydrological Variable	**Analysis Period**
	35 - 40 years up to 2000s
Annual Runoff	↑
Low flow magnitude	_
Low flow duration	_
High flow magnitude	↑
High flow duration	↑
Annual maximum flow	↑
POT frequency	↑
Winter Runoff	↑
Spring Runoff	_
Summer Runoff	_
Autumn Runoff	↑

Table 2 Summary of Trend Results for data from 109 stations from the Canadian RHBN

Hydrological Variable	**Analysis Period**		
	1969 - 2008	**1959 - 2008**	**1949 - 2008**
January mean discharge	↑	↑	↑
February mean discharge	↑	↑	
March mean discharge	↑	↑	↑
April mean discharge	↑	↑	↑
May mean discharge	↓	↓	↓
June mean discharge	↓	↓	↓
July mean discharge			↓
August mean discharge	↓	↓	↓
September mean discharge	↓	↓	↓
October mean discharge			
November mean discharge			
December mean discharge	↑		
Annual mean discharge	↓		↓
Peak discharge	↓	↓	↓
Date of Peak	↓	↓	↓
Low Flow	↑↓	↓	↑↓
Date of Low Flow Date	↓		↓

Table 3 Summary of trend studies drawn from the literature

Continent	**# of Papers**	**Network Status**				
		RHN	**RHN ~**	**RHN +**	**RHN + Non**	**Non-RHN**
Africa	4					4
Asia	23		3			20
Europe	26	2	5			19
N. America	68	36	3	1	8	20
S. America	3		1			2
Other	4				1	3
Total	128	38	12	1	9	68

Note:

RHN = RHN (Reference Hydrologic Network) stations only

RHN ~ = RHN-like (nearly natural; no impoundments; minimal land use change)

RHN + = RHN plus RHN-like

RHN + Non = RHN stations plus non-RHN stations

Non-RHN = Non-RHN stations only (none or only some of the typical criteria for an RHN were explicitly considered)

Figure Captions

Figure	Caption
1	Results of trend tests applied to the Benchmark Network, 1969 – 2008. a) winter, b) spring, c) summer, d) autumn.
2	Winter-spring streamflow timing trends in eastern North America, 1953-2002. Upper panel indicates significance of changes and lower panel indicates magnitude of changes.